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Impact of low-carbon electricity development on carbon emissions in China

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Citation

Yuan, R. (2018, May 17). *Impact of low-carbon electricity development on carbon emissions in China*. Retrieved from <https://hdl.handle.net/1887/62046>

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Author: Yuan, R.

Title: Impact of low-carbon electricity development on carbon emissions in China

Issue Date: 2018-05-17

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PhD thesis, Leiden University, The Netherlands

ISBN: 978-94-6182-892-7

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Cover designed by Rong Yuan

Printed by Printenbind, www.printenbind.nl

Impact of low-carbon electricity development on carbon emissions in China

PROEFSCHRIFT

Ter verkrijging van de graad van Doctor aan de Universiteit Leiden,
op gezag van de Rector Magnificus prof. mr. C.J.J.M Stolker,
volgens besluit van het College voor Promoties,
te verdedigen op donderdag 17 mei 2018,
klokke 11.15 uur

Door

Rong Yuan

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Geboren te Urumqi, China, in 1990.

Promotiecommissie

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Chapter 1

General introduction

This chapter introduces China's carbon emission problem, with a focus on the decarbonization of China's electricity sector through the development of low-carbon electricity (LE) technologies. It also introduces the research questions which are addressed in this thesis.

1.1. The importance of decarbonization of China's electricity sector

With rapid economic growth in China, its carbon emissions have been growing rapidly. Since joining the World Trade Organization (WTO) in 2002, China's carbon emissions increased from 3472 to 9265 million tonnes (Mt) during the period 2002-2015, at an annual rate of 13% (Shan et al., 2017). China's total carbon emissions overtook the United States in 2006 (BP Statistical Review of World Energy 2017). At present, China is the largest emitter of carbon in the world (Zhao et al., 2018). China's emissions accounted for about 27.5% of the world's total in 2014 (Du and Lin, 2018). The International Energy Agency (2013) forecast that by 2035, China's percentage of the world's total carbon emissions will be approximately 33% (Hao et al., 2016). China is also a net emission exporter through trade (Kanemoto et al., 2014). During 2002-2011, the accumulated emissions embodied in exports accounted for approximately 30% of the total carbon emissions in China (Liu et al., 2017). From 1990 to 2008, 75% of the growth in consumption-based emissions of Annex B countries were from China's export-embodied emissions (Peters et al., 2011). The emission savings in carbon abating countries have been partly compensated by net emission transfers from China, leading to the so-called carbon leakage effect (Paroussos et al., 2015, Chang, 2016).

China has been under pressure from the international community to reduce its carbon emissions. To reduce emissions, in 2009, China set a 2020 target to reduce CO₂ emissions per unit of Gross Domestic Product (GDP) by 40-45% from the 2005 level (NDRC, 2014). In November 2014, in the U.S.-China Joint Announcement on Climate Change, China guaranteed that the carbon emissions per unit of GDP will reduce even further by 2030, by 60%-65% compared to the 2005 level, and that the total emissions will peak around 2030 (Shao et al., 2016). In the 13th Five-Year Plan (2016-2020), China formulated mitigation targets for reducing aggregated energy intensity and aggregated carbon emission intensity by 15% and 18% by 2020, respectively (NDRC, 2016). Given these developments, and the future international targets, studies on China's carbon emissions are both important and relevant.

The electricity sector is an important area of focus, since it is a large contributor to the total emissions. The CO₂ emissions from electricity generation in China increased from 588 to 3631 Mt during the 1991-2014 period, with an increasing share from 24.94% of the total energy-related carbon emissions in 1991 to 36.88% in 2014 (Hou and Hou, 2018). China's generation capacity per capita reached 1 KW at the beginning of 2015, which happens to be the global average (CEC, 2015). From 2002 to 2016, China's electricity consumption increased from 1639 TWh to 5920 TWh (NEA, 2017). CEC (2015) reports that the total electricity consumption is expected to reach 7700 TWh by 2020, corresponding to a consumption per capita of 5570 KWh by 2020. In 2016, the energy

consumption of the electricity sector reached 1303 million tonnes of oil equivalent, accounting for about 43.34% of the total energy consumption (IEA, 2017). Coal is the dominant energy in China's electricity sector and accounted for 79.97% of the total in 2016 (IEA, 2017). Since the main source of emissions results from the burning of fossil fuels, the increase in electricity consumption will unavoidably lead to the growth of China's carbon emissions. The carbon emissions from China's electricity sector increased by 277.42% from 1995 to 2014 (Wang et al., 2018). Since the relevance of the electricity sector with respect to carbon emission mitigation is so obvious, the decarbonization of China's electricity sector is crucial to realizing China's emission reduction targets.

1.2. The development of low-carbon electricity

Since the electricity sector comprises the most important sector of emissions, it continues to be a major focus of attention for national policy makers. A key part of this attention has been on the development of LE technologies. In September 2007, the government of China announced a target to double the share of renewable energy in the total primary energy consumption, from 8% in 2006 to 15% in 2020 (NDRC, 2007). The 13th Five-Year Plan (2015-2020), goes even further, with a target to increase non-fossil energy to 20% of the total primary energy consumption by 2020 (Zhang et al., 2017). Targets for mid-century were set in the 2016, China's Energy Production and Consumption Revolution Strategy (2016-2030), stipulating that the share of non-fossil energy should be higher than 50% of total primary energy consumption by 2050.

China's energy policy has resulted in the rapid growth of LE generation in recent years. The proportion of non-fossil energy in total primary energy consumption reached 11.2% in 2014 (He, 2015). Since 2000, China's hydropower saw a rapid development. In 2004, the installed capacity of China's hydropower surpassed 100 GW, and China possessed the world's largest number of dams. Apart from having the world's largest installed capacity for hydropower, China also became a crucial player on innovation in hydropower technology in 2015 (Li et al., 2018). Due to the implementation of China's Renewable Energy Law after 1 January 2006, wind and solar power have witnessed tremendous growth in both installed capacity and generation. The cumulative installed capacity for wind power increased from 1GW in 2005 to 149 GW in 2016, with an increasing share of the total electricity generation from 0.07% in 2005 to 4.02% in 2016 (CEC, 2017). The cumulative installed capacity for solar power grew from 70 MW in 2005 to 77 GW in 2016, with an increasing proportion from almost 0% of the total electricity generation to 1% in 2016 (CEC, 2017). Clearly, there are carbon benefits from increasing LE deployment. However, there is much to do in terms of understanding the magnitude and distribution of these benefits across China spatially, and through the economy.

Research on the carbon impact of Chinese LE development has been a fast-growing area of attention in recent years. Several attempts have been made to explore the impact of LE development on future emissions. For instance, Zhao et al., (2017) deployed Life Cycle Assessment (LCA) methods to investigate the impact of the substitution of wind power for coal-fired power. Wu et al., (2017) used CGE models to predict the impact of national LE development policies on the existing carbon market and economy. Song et al., (2015a, b) combined a dynamic simulation model with an input-output (IO) framework to assess the contribution of LE development to achieving emission reduction targets. There are also a few ex-post studies observing the relationship between LE development and the trend of emissions using econometric analysis techniques (Li and Yang, 2016, Wang and

Li, 2016) and decomposition methods (Dong et al., 2016, Lima et al., 2016, Tian and Yang, 2016). These studies have provided empirical evidence showing that LE development has played a key role in reducing China's carbon emissions. However, there is a significant variation of LE impacts between China's different provinces due to significant differences in resource endowments. Currently, some studies have compared effects of LE development across regions. For example, Li et al., (2017) introduced a multi-region Computable general equilibrium (CGE) model, which incorporated three regions of China (eastern, central and western regions), to investigate regional effects of LE policies in China. However, they did not describe the detailed effects of various types of LE technologies. Moreover, they did not explore the pattern of LE impacts, that is, how LE development affects carbon emissions across regions in China. The carbon impact of LE development can be ascribed by many modes. For example, inter-regional electricity transmission represents a flexibility mechanism that allows regions to more efficiently share LE resources (Abrell and Rausch, 2016). Therefore, there is a clear need for research which assesses the carbon impact of LE development through a multi-regional analysis that can identify the pattern of carbon impacts of China's LE development.

1.3. The relation to carbon emissions embodied in exports

There have been several studies evaluating the carbon emission impacts from LE developments in China. For example, Zhou et al., (2012) analyzed the contribution of non-fossil energy to achieving China's energy and climate targets for 2020. The result showed that the use of non-fossil energy contributes to 17-19% of the total emissions reduction target in 2020. Duan (2017) evaluated the climate change benefits of the substitution of wind for coal-fired electricity, and investigated the long-term emission mitigation potential of wind power expansion. The result showed that emission reductions associated with the substitution of wind power for coal-fired power increase with the expansion of wind power market. Li et al., (2017) explored the regional effects of promoting non-fossil fuels on the carbon emissions in China, showing that all regions demonstrate declining trends in carbon intensity with increasing share of non-fossil fuels. There is general agreement that the development of LE could reduce China's carbon emissions. However, most of these studies assessed the impact of LE development on the total national carbon emissions in China, but did not provide a clear conclusion about the historical impact of LE development on the carbon emissions embodied in China's exports. Therefore, in this thesis, the impact of LE development on China's export-embodied carbon emissions are explored.

Previous literature on China's export-embodied emissions mainly focused on the balance of carbon emissions embodied in trade (Dong et al., 2017, Li et al., 2017, Zhang et al., 2017), and analyzed the driving forces of emissions embodied in China's international trade using Multi Regional Input-Output (MRIO) models (Duan and Jiang, 2017, Wu et al., 2016, Zhao et al., 2016). Liu et al., (2015) ascertained that adjusting the energy structure in a few number of provinces could reduce the total emissions embodied in China's exports. These studies have enhanced the understanding of the drivers of export-embodied carbon emissions. However, they only relate their findings to the carbon impact of the change of the share of fossil fuel in the total primary energy consumption, but did not identify the difference in the carbon impacts of various LE technologies. Moreover, limited work has been undertaken to assess the impact of LE development on China's export-embodied emissions at the provincial level.

China shows a great deal of regional variety, both in terms of LE resource endowments and the share of exports in the total GDP. Exports are concentrated in the developed provinces, such as Guangdong, Shanghai, Jiangsu and Zhejiang. However, the levels of LE penetration in these provinces are lower than those of inland provinces (e.g. Sichuan, Guangxi and Yunnan) (see Chapter 3). In order to optimally develop LE in appropriate regions, China has enhanced the inter-regional electricity transmission such that the regions with little LE resources can utilize the LE transmitted from the regions with abundant LE resources (Wang et al., 2016). In 2014, inter-regional electricity transmission was up to 391.2 billion kWh, an annual increase of 10.89% (Zeng et al., 2016). Since inter-regional electricity transmission is critical, an analysis of carbon impacts of LE development at the regional level needs to consider inter-regional electricity transmission capacity. Moreover, since the development of LE in one region could affect carbon emissions embodied in other regions' exports via inter-regional economic linkages (Feng et al., 2013), it is necessary to estimate inter-regional spillover effects of LE development on carbon emissions embodied in exports.

1.4. Carbon impact of expansion of low-carbon electricity infrastructure

The carbon impact of LE development has been extensively examined, with a consensus on the carbon benefit of LE operation. However, LE technologies consume more energy and materials and induce more carbon emissions in installation processes compared to fossil-fuel electricity technologies (Hu et al., Wiedmann et al, 2010, 2011, Phel et al., 2017). Thus, the carbon impact of LE development relates not only to the operational impact of LE expansion, but also to the carbon impact of the expansion in LE infrastructure. Moreover, given China's regional diversity, there are significant differences in the carbon impact of LE infrastructure across China. Therefore, an analysis of the characteristics of carbon impacts of LE investments in different provinces can provide implications for regional energy management.

Inter-regional economic linkages are also an important factor for tracing the carbon impact of LE investments, as inter-regional carbon flows pinpoint regions in which the supply chain of LE investments can be improved. For example, considering that the western and central regions are major suppliers of intermediate inputs for the eastern region (Hong et al., 2016), the improvement of manufacturing technologies in the western and central regions could reduce the carbon impact of LE investment in the eastern region through providing low-carbon intermediate products (see Chapter 4). Therefore, recognizing the hidden linkages and carbon flows embodied in the inter-regional trade is of great importance to exploring carbon impacts of LE investments.

Finally, China's mitigation scenarios as developed by the International Energy Agency have shown that switching from fossil-fuel electricity technologies to LE technologies is a key element of decarbonization strategies (IEA, 2017). Yet, they do not provide estimations of the "carbon overhead" related to creating a LE infrastructure. Since China will need to build a large amount of low-carbon electricity infrastructure to hit climate targets, and because this infrastructure can be more carbon intensive to build (not to use), China will need to plan for a certain amount of the remaining carbon budget to be taken up with this expansion. This can be called "carbon overhead" of LE infrastructure. In other words, the "carbon overhead" refers to the additional environmental cost in the investment stage of LE, while LE development could bring carbon emission mitigations

in the operation stage through increasing the share of LE in the total primary energy consumption. Since electricity supply will undergo a transformation towards LE technologies in the future, the carbon impact of LE investments is expected to continue to increase. This means that the “carbon overhead” from LE infrastructure might be a constraint on LE development in the future. Moreover, the impact of LE investments on carbon emissions cannot be assessed statically, since for such relatively new technologies learning curves can be expected to drive down the carbon impact of LE investments (Aste et al, 2016).

1.5. Methods for analyzing the carbon impact of low-carbon electricity development

Single-region IO models provide an approach to modeling a regional economy within IO framework, however, they do not identify inter-regional connections. In order to capture the various economic linkages among several regions in a multi-regional economy, MRIO models were suggested by Chenery (1953) and Moses (1955). Leontief and Strout (1963) developed the gravity-model method to calculate the inter-regional flows in a connected-region MRIO model, containing counterparts to the intra-regional technical coefficients matrices and the inter-regional technical coefficients matrices. Many studies have shown that a Multi-Regional Input Output (MRIO) approach is useful in analyzing China’s carbon emissions at the regional level (Feng et al., 2013, Tian et al., 2014). A major advantage of MRIO is that it takes into account regional production and emission characteristics. Particularly, MRIO analysis can be used to identify how production in one region drives production and carbon emissions in other regions via supply chains (Wiedmann et al., 2010, Meng et al., 2013).

In terms of assessing the carbon impact of LE development in China, an MRIO model is a comprehensive approach in which the entire carbon footprint of LE development can be considered. This means that not only the intra-regional carbon impact of LE development can be taken into account, but also the indirect carbon impact of LE development in other regions. Therefore, the results of MRIO analysis can provide holistic insights into the regional and sectoral interactions through the whole supply chain of LE sectors, which is beneficial for policy makers to understand the inter-regional carbon flows induced by LE activities. In principle, China’s National Bureau of Statistics only publish official IO tables for individual provinces in China, and thus a problem is the estimation of the transactions between regions. However, some researchers have compiled MRIO tables by constructing cross-regional and cross-sectoral matrices. Currently, China’s MRIO tables for 2002, 2007 and 2010 are available with all 30 Chinese provinces. However, different researchers compiled these MRIO tables at different sector details based on the availability of data. The MRIO table for 2002 is for 21 Chinese sectors (Shi and Zhang, 2012), while the MRIO tables for 2007 and 2010 are for 30 sectors (Liu et al., 2012; 2014). Thus, the sectors in the three MRIO tables are often aggregated into 21 sectors. Moreover, the carbon emissions by sector can be estimated based on China Energy Statistical Yearbooks (CESY) (NBS, 2003, 2008, 2010, 2012, 2015). This thesis introduces MRIO models and more details are in Chapters 3, 4, and 5.

There have been few studies analyzing the carbon impacts of region-specific LE implementation scenarios for China with MRIO models. One of the main reasons is that the available Chinese MRIO only has one, average electricity generation sector by region. For assessments on LE, different types of electricity production sectors must be discerned

in an MRIO table. Some researchers disaggregated the MRIO table itself to obtain disaggregated electricity sub-sectors (Lindner et al., 2012), however, this will induce parametric and systematic error (Wiedmann et al., 2011). This can be solved by expanding the existing Chinese MRIO into a multi-regional economic-energy hybrid model which links energy data in physical units to a Leontief matrix in monetary units (Guevara and Rodrigues, 2016) (see Chapter 3). Through this approach, energy types can be disaggregated according to the amount of electricity generation in energy units, while the aggregated electricity sector in the MRIO table still remains in monetary units. The hybrid model not only has the characteristic of the comprehensiveness of IO models, but also provides the accuracy from energy data of inter-regional electricity generation and transmission. Furthermore, within the IO framework, Hedi, (2017) provided a final-demand approach to assess the impact associated with an exogenous demand stimulus in an electricity sub-sector (e.g. an investment activity in wind power). Using this approach, a demand stimulus of an electricity sub-sector can be introduced into the MRIO table by constructing a demand vector that reflects the changes of the inputs in the existing sectors of the MRIO table. Therefore, MRIO tables do not need to be disaggregated even for the estimation of the impact of new demand stimulus of the LE sector. These two approaches combined help to overcome a major limitation of previous MRIO analyses on this topic (see Chapter 4).

1.6. Research questions

From the above, we can deduce a number of issues. First, as many authors have shown, the structure of China's energy system has enormous implications on the carbon embodied in the products and services produced and used in and exported by China. So, a study of the impact Chinese LE development on export-embodied carbon emissions should contribute to providing fundamental information for investigating export-embodied emission reduction potentials in China. Yet, few authors have taken into account LE developments from a regional perspective in China. A main reason for this is lack of detail in the electricity production sector in the available Chinese MRIO tables. However, this problem can be solved by a hybrid unit MRIO mode (see Chapter 3) and a final demand approach (see Chapter 4), as described above. At the same time a regional perspective is highly relevant, since the implementation of LE and the production of products and services for use in China and for exports are not at evenly distributed over the various Chinese regions. It is also appreciated that LE investments are usually more carbon intensive than investments in traditional electricity generation. As indicated, most scenarios do not take this factor into account (e.g. IEA, (2017)), let alone from a region-specific perspective. Against this background, this thesis aims to answer the following research questions:

1. *How are carbon emissions distributed across sectors from the perspective of inter-sectoral linkages? What spillovers occur via supply chains, particularly between the electricity sector and other production sectors?*
2. *How will the development of low-carbon energy across regions impact carbon emissions embodied in China's exports? What is the role of electricity transmission and supply chains in regional emission reductions?*
3. *How do the carbon emissions from investments in LE infrastructure compare to the reduction of carbon emissions during the use of LE? How are the carbon impacts of*

this infrastructure distributed within China?

4. *How will the carbon impact from the expansion of LE infrastructure evolve in the future?*

1.7. Outline of thesis

As described above, an MRIO approach has many advantages in analyzing the linkage effects between regions in China. However, few studies have applied an MRIO approach to the carbon impacts of LE development in China at the regional level, because no sector captures LE generation in the existing Chinese MRIO table. To solve this problem, in this thesis, the MRIO model is improved by developing a multi-regional economic-energy hybrid model, such that LE generation in energy units can be added to the Chinese MRIO tables in monetary units. Moreover, to investigate the carbon impacts of installing LE generation system, this thesis also presents a demand-driven MRIO approach in which the inputs for LE investments are allocated among the sectors existing in the MRIO tables based on the LE investment structure. Using these approaches, the carbon impact associated the LE expansion in the operational and investment stages are separately estimated and the research questions can be addressed.

The thesis consists of 6 chapters. This chapters, Chapter 1, is a general introduction, providing a background on the general status of China's carbon emissions. The importance of developing LE electricity technologies is highlighted. After reviewing most relevant studies on the carbon impact of LE development, the research questions and outline of the thesis are discussed.

Chapter 2 answers research question 1. It provides an overview of China's carbon emissions from a multi-sectoral perspective, focusing on the temporal variations of carbon emissions and the contributions of various sectors. By treating each sector as a subsystem, the different emission components (internal, feedback, spillover and direct) of different sectors are assessed to explore the carbon linkages of each sector with the rest of the economy. The investigation of the carbon linkages between China's sectors provides decision makers a comprehensive picture for formulating feasible emission mitigation policies.

Chapter 3 answers research question 2. It analyzes the impact of LE development on carbon emissions embodied in the exports of China's 30 provinces during 2002-2014. A multi-regional economic-energy hybrid model is developed, such that the carbon impact of LE electricity can be categorized into the intra-regional effect, electricity transmission effect and supply-chain effect. The historical, export-embodied emissions in China is compared against a counterfactual in which the LE expansion of 2002-2014 did not take place. The results are used to better understand the patterns of carbon impacts of LE development across provinces and over the years, given the dynamic nature of China's economic development and the heterogeneity of China's regions.

Chapter 4 answers research question 3. It focuses on the carbon impact of LE infrastructure expansion using a demand-driven MRIO model. Historical emissions induced by LE investments are compared with a counterfactual scenario without LE investments to gain insight into the carbon impact of LE investments at the provincial level. The estimated carbon impact of LE investments is compared with the operational impact of LE. Moreover, in order to summarize the patterns of regional carbon impacts of

LE investments, the intra-regional and inter-regional impacts of LE investments are separately assessed.

Chapter 5 answers research question 4. It projects the carbon impact of LE investments during 2015-2040. Based on the declining trend of historical carbon intensity of LE installation, experience curves are constructed to project the carbon intensity of LE installation up to 2040. By combining predicted carbon intensity of LE installation with the predicted cumulative installed capacity under well-known scenarios from national and international bodies, the carbon impact of LE investments during 2015-2040 is projected. The results provide indications on the carbon performance of LE investments in the future.

Chapter 6 summarizes the answers to the research questions posed above and develops a general discussion focusing on the directions of future research.

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Chapter 2

The evolution of inter-sectoral linkages in China's energy-related CO₂ emissions from 1997 to 2012

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Published in *Energy Economics*, 69, 404-417

Abstract

Energy-related CO₂ emissions in China have been extensively investigated. However, the mechanisms of how energy-related emissions are driven by inter-sectoral linkages remains unexplored. In this paper, a subsystem input-output model was developed to investigate the temporal and sectoral changes of emissions in China from 1997 to 2012. We decomposed total emissions into internal, spillover, feedback, and direct components. Our results show that the equipment manufacturing, construction and services sectors are the main sources of emissions during the whole period, which have a larger spillover component, primarily through indirect upstream emissions in the heavy-manufacturing, transportation, and power sectors. The emissions from the power and transportation sectors are dominated by direct rather than the spillover emissions. The shares of the feedback and internal components in the heavy manufacturing sectors were significantly higher than those of other sectors. Our results suggest that further addressing carbon emissions along the supply chain of equipment manufacturing, construction and services sectors, and improving technologies in the heavy manufacturing and power sectors holds important future opportunities for curbing the rapid growth of carbon emissions in China.

Keywords: CO₂ emissions; feedback and spillover effects; subsystem input-output model; sectoral analysis; China.

1. Introduction

Accompanying extraordinarily rapid economic growth, China became the leading CO₂ emitter in the world in 2006. In 2014 Chinese emissions already accounted for 30% of the world total, twice as much as the second-largest, the United States, at 15% (Liu, 2015). In response, China has committed to cut emission intensity (kg CO₂eq/Yuan) by 40-45% in 2020, and by 60-65% in 2030, both figures relative to a 2005 baseline (Xinhua net, 2009; NDRCC, 2015). Furthermore, the government has a goal to peak absolute CO₂ emissions by 2030 and increase the share of non-fossil fuel energy to 20% in the same year (CDNDRC, 2014). In order to meet these national goals in an efficient and cost-effective manner, specific policies targeting the economic sectors with more opportunities to reduce carbon emissions will have to be developed. As such, further information on sectoral emissions is of the utmost importance.

Several sectors already have their own reduction targets. For instance, the energy sector has a standing commitment to reduce coal consumption to 65% of total primary energy consumption by 2017 (The State Council, 2013). Within the Energy Development Strategy Action Plan (2014-2020), the installations of wind and solar power in 2020 are

expected to reach 200GW and 100GW, respectively (The People's Republic of China, 2014; Yang et al. 2016). The refining, coking, non-metallic mineral, and chemical sectors have goals in terms of energy consumption per unit of value added (The State Council, 2011). The allocation of sectoral emission reduction targets has focused to a great extent on traditional, energy-intensive sectors. There is still a widespread under-appreciation of the importance of reductions in non-energy intensive sectors (Zhang et al., 2015). However, the achievement of national targets will depend on how emissions from each sector will interact with those from the rest of the economy (Zhao et al., 2016). Accordingly, understanding how embodied carbon emissions are driven throughout the economy is both important and urgent for developing differentiated and practical emission reduction targets.

Previous research has analyzed carbon emissions in China from both single-sectoral and multi-sectoral perspective. Single sector studies include, Li et al. (2016), focused on the cement sector and developed an integrated assessment model to estimate the reduction potentials through different carbon mitigation pathways. Lin and Zhang. (2016), also focusing on cement, applied the logarithmic mean Divisia index (LMDI) method to examine carbon intensity, energy intensity, energy structure, sector scale, and labor productivity. In the mining sector, Shao et al. (2016) adopted the generalized Divisia index method (GDIM) to investigate drivers of CO₂ emissions changes, and conducted a scenario analysis to identify mitigation pathways. In the power sector, Khanna et al. (2016) used an energy end-use model to evaluate energy and carbon emissions reduction potential to 2050, and Su et al. (2016) calculated provincial CO₂ emissions considering the fuel mix of exported electricity. In the iron and steel sector, Xu et al. (2016b) developed a Material Flow Analysis to estimate the CO₂ emissions; Peng et al., (2016) used global, multi-regional input-output (MRIO) and structural path analysis to single out important supply chain paths; and, Lin and Wang (2015) used stochastic frontier analysis to evaluate CO₂ emission reduction potential. Finally, in the freight sector, Hao et al. (2015) established a bottom-up model to forecast trends of energy consumption and GHG emissions. Such single-sectoral analyses are very valuable in themselves but they do not take into account the possibility of synergistic effects, with emissions occurring elsewhere in the economic landscape, when a policy targets a specific sector.

Multi-sectoral studies have focused on cross-sectoral comparisons among various industries or sectors, usually with a continuous time series. For example, Yu et al., (2016) proposed a multivariable, environmental learning curve panel model to estimate the emission abatement potential of 43 sectors. There have been a number of studies employing the LMDI method to break down sectoral contributions to GHG emissions. For example, Wang and Zhao (2016) studied the changes of carbon emissions in high, mid, and low energy-consumption sectors for 1996-2012. Xu et al. (2016a) explored emissions during different periods and from different sectors. Liu et al. (2015a) extended the LMDI methodology to analyze the changes in carbon intensity in 12 sub-sectors in China's industrial sector. Yan and Fang (2015) investigated the impact of emissions in 42 sub-sectors of the Chinese manufacturing industry for 1993-2011. Xu et al. (2014) analyzed the variations in sectoral emissions from 1996 to 2012. Many studies have focused on CO₂ emissions in China's sectors, but previous work does not examine the inter-sectoral linkages of CO₂ emissions from the perspective of supply chains (Ouyang and Lin, 2015; Kang et al., 2014; Ren et al., 2014). Thus, they may over-estimate the responsibility of the energy-intensive sectors and under-estimate the responsibility of non-energy intensive

sectors (e.g., services) when the full effect of their supply chain is considered. In other words, although significant efforts for emission reduction in the energy-intensive sectors has been made, the non-energy intensive sectors' demand for energy-intensive products may indirectly cause substantial CO₂ emissions in the upstream energy-intensive sectors. We therefore believe a complete analysis of sectoral CO₂ emissions propagating throughout the whole supply chain is required.

The trade linkages in different regions that influence China's emissions have been investigated. The regional linkage effect is divided into the spillover and feedback effect (Round, 2001). The spillover effect measures the indirect effect of final demand changes in a specific region on the CO₂ emissions of other regions. The feedback effect then measures the increase in emissions occurring in the original region resulting from spillovers from other regions. Some studies have examined spillover and feedback effects of carbon emissions occur in multiple regions of China (Zhang and Zhao, 2005; Meng et al, 2013; Tang et al., 2015), but we are not aware of any comparative analysis of spillover and feedback effects of Chinese sectoral emissions. It is then fruitful to examine sectoral linkages in China with more detail.

Several studies have applied a subsystem input-output methodology to investigate sectoral emissions, taking into account the structure and sectoral linkages of different national economies. Subsystem models consider an individual sector, or group of sectors, as a subsystem and then study its production relations with the rest of the economy, while remaining embedded in the full production system. Previous studies are focused on the carbon emissions embodied in a group of sectors (Alcantara and Padilla, 2009; Butnar and Llop, 2011; Rachel, 2014; Matias and Thomas, 2014; Yuan and Zhao, 2016; 2017). Llop and Tol (2013) expanded the approach to sectoral based emissions for the whole Irish economy, but did not investigate feedback mechanisms of emissions in detail. Alcantara et al., (2017) extended the model in a different way to uncover the different components of total consumption-based emissions in the different sectors in Spain. They clarified the relationship between inter-sectoral spillover of CO₂ emissions and the whole supply chain and addressed inter-sectoral feedback of CO₂ emissions but only for a single year. Here, we use the method from Alcantara et al. (2017) and extend this approach to a time-series analysis.

Final consumption of one sector leads to both its own carbon emissions and to emissions in other sectors (Liu et al. 2012, Alcantara and Padilla, 2009) and, according to Alcantara et al. (2017), the sum of these emissions can be decomposed in four components: direct, internal, spillover and feedback, which we now briefly review. Direct emissions are the corresponding change in the emissions caused by a small, exogenous change in the final consumption. For example, an increase in the final consumption of chemical products will generate extra CO₂ emissions in the chemical sector simply because the increase causes a direct effect of the same amount on the output of the chemical sector. Internal emissions are defined as carbon emissions arising only from the intermediate consumption of own inputs for the final consumption itself. For example, to satisfy the final demand of chemical sector, the chemical sector buy its own inputs for intermediate consumption, which will generate new carbon emissions in the fabrication of chemicals. However, for the fabrication of chemicals, the chemical sector requires inputs from other sectors along a supply chain, leading to extra CO₂ emissions in the production processes of other sectors: these are inter-sectoral spillover effects. Spillover effects are defined as the indirect impacts of the final consumption of one sector on the emissions occurring in

the production processes of other sectors arising from additional inputs requirements. If a specific sector has greater spillover effects than others, then this sector has a strong pulling effect on the total carbon emissions in China by stimulating production in other sectors and should therefore be taken into account when designing an emission reduction policy. Additionally, there might exist a loop in the economic network in which the chemical sector providing inputs to a sector further upstream in its own supply chain. If that is the case, there will be further CO₂ emissions taking place in the chemical sector: these are inter-sectoral feedback effects. Feedback effects are defined as further emissions generated in the intermediate consumption of one sector caused by an additional input stimulus arising in the other sectors. For example, if the chemical sector requires additional inputs from the other sectors, in turn, the additional production in the other sectors will be reflected in the intermediate consumption of the chemical sector through the further demand for additional inputs. Therefore, if a specific sector has greater feedback effects than others, then emission changes in this sector depend more strongly on its own demand.

Given the existence of a knowledge gap in the current understanding of inter-sectoral carbon linkages in the Chinese economy, and the importance this presents to policy making, here we use subsystem input-output modelling to conduct a time-series analysis (1997-2012) of multi-sectoral emissions in China. For the purpose of the study we investigate the four emission components outlined above: direct, internal, spillover, and feedback. Our study differs from those reviewed above as we explore how sectoral linkages of a given sector with the rest of the economy change over time, and compare the changes in inter-sectoral spillover and feedback emissions. Such analyses can not only clarify how emissions are created and distributed across sectors, but also reveal trends and disparities within sectors. We are thus able to obtain a thorough understanding of sectoral emissions features, singling out key emission sectors and providing new insights for allocating Chinese sectoral emission reductions.

The remainder of this paper is organized as follows: Section 2 introduces the subsystem input-output model of CO₂ emissions and data processing; Section 3 offers the empirical results of CO₂ emission multi-sectoral analysis; Section 4 discusses the policy implications of this work; and, finally we offer some conclusions.

2. Methodology and data

2.1. Subsystem input-output model

Sectoral carbon emissions are based on fossil fuel consumption using IPCC guidelines (IPCC, 2006). We do not include emissions from non-energy use and industrial processes. Carbon emissions (e) are calculated as

$$e = EF \times EC \quad (1)$$

where EF is the fossil fuel type specific equivalence CO₂ emission factor (based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories) and EC is the physical amount of fossil fuel consumption (based on the energy statistics data).

The standard Leontief (1936) model is given

$$x = Ax + y \quad (2)$$

where x is a $(n \times 1)$ vector of total output whose element x_i is the output of sector i , y is a $(n \times 1)$ vector of final demand whose element y_i is the final demand of sector i ; and A is a $(n \times n)$ matrix of technical coefficients, where the characteristic element a_{ij} shows the consumption of inputs, in money terms, from sector i per unit of output, in money terms, of sector j . That is:

$$a_{ij} = \frac{x_{ij}}{x_j} \quad (3)$$

The solution of the system is then given by:

$$x = (I - A)^{-1}y \quad (4)$$

where $(I - A)^{-1}$ is the well-known Leontief inverse, and I is the identity matrix. To estimate CO₂ emissions, we introduce the carbon emission coefficients $c_i = e_i/x_i$ (i.e. CO₂ emissions per unit of economic output) for all economic sectors. Let c_i denote the carbon emission coefficient of sector i , then the CO₂ can be estimated as follows:

$$e = c'Ly \quad (5)$$

where e is a $(n \times 1)$ vector of total CO₂ emissions embodied in goods and services generated by final demand, c is a $(n \times 1)$ vector of carbon emission coefficient for all economic sectors, $(I - A)^{-1} = L = [l_{ij}]$ is the Leontief-inverse, $\hat{y} = \text{diag}(y)$ is the diagonal vector of y .

We define emissions embodied in the total output of sector i as output-induced emissions, which can be calculated as follows:

$$e_i = c_i l_{ii} y_i + \sum_{i \neq j} c_i l_{ij} y_j = e_{ii} + \sum_{i \neq j} e_{ij} \quad (6)$$

where e_i is emissions released from sector i driven by China's total final demand. By symmetry, the total emissions induced by the final demand of sector i is calculated as

$$e'_i = c_i l_{ii} y_i + \sum_{i \neq j} c_j l_{ji} y_i = e_{ii} + \sum_{i \neq j} e_{ji} \quad (7)$$

where e'_i is the amount of carbon emissions that all sectors have to produce to obtain the final demand of sector i . We define this as demand-induced emissions. Note that e_{ij} and e_{ji} both reflect inter-sectoral emission transfer, but they have different meanings. e_{ij} in Eq. (6) is the direct CO₂ emissions caused by sector j in sector i , which reflects the distribution of emissions in the demand chain of sector i . While e_{ji} in Eq. (7) is the embodied CO₂ emissions of sector j induced by the final demand of sector i , which reflects the distribution of emissions in the supply chain of sector i .

Next, we transform Eq. (7) to decompose demand-induced CO₂ emissions resulting from various effects. The first step is to decompose direct and indirect demand effects. Direct demand effects are those that occur within the sector and are directly caused by final demand. Indirect demand effects are total minus direct demand effects and can occur either in the sector itself, or further upstream along the supply chain:

$$e'_i = c_i y_i + \left(c_i l_{ii} + \sum_{i \neq j} c_j l_{ji} - c_i \right) y_i \quad (8)$$

where $c_i y_i$ shows the direct carbon emissions caused by the final demand of sector i and $(c_i l_{ii} + \sum_{i \neq j} c_j l_{ji} - c_i) y_i$ is the indirect carbon emissions caused by the final demand of sector i .

Indirect sectoral carbon emissions can be further decomposed into intra-sectoral indirect emissions (occurring in the same sector) and inter-sectoral spillover emissions (occurring in other sectors). The total demand-induced emissions occurring in sector i , denoted by e_i , can be decomposed as follows:

$$e'_i = c_i y_i + c_i (l_{ii} - 1) y_i + \sum_{i \neq j} c_j l_{ji} y_i \quad (9)$$

where $c_i y_i$ reflects an additional growth of direct carbon emissions in the sector i when the final demand of sector i increases one unit (the direct effect identified above). The second term, $c_i (l_{ii} - 1) y_i$ shows the intra-sectoral indirect emissions generated in the production of intermediate inputs by the sector i required to satisfy its final demand (the intra-sectoral indirect emissions). The final term, $\sum_{i \neq j} c_j l_{ji} y_i$ shows the emissions occurring in sector i which result from inter-sectoral demands aimed at delivering final demand of sectors (spill-over effect).

Considering the matrix L is determined by $(I - A)$ and is the inverse of $(I - A)$, the elements of the main diagonal of the Leontief inverse can be expressed as follows:

$$l_{ii} = (1 - a_{ii})^{-1} \left(1 + \sum_{i \neq j} a_{ij} l_{ji} \right) = (1 - a_{ii})^{-1} + (1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} \quad (10)$$

and $(l_{ii} - 1)$ can be transformed as follows:

$$\begin{aligned} l_{ii} - 1 &= (1 - a_{ii})^{-1} \left(1 + \sum_{i \neq j} a_{ij} l_{ji} \right) - 1 \\ &= [(1 - a_{ii})^{-1} - 1] + (1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij} l_{ji} \end{aligned} \quad (11)$$

Thus, the intra-sectoral indirect emissions can be further decomposed in two separate components, internal and feedback effects, according to the following equation:

$$c_i(l_{ii} - 1)y_i = c_i[(1 - a_{ii})^{-1} - 1]y_i + c_i(1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij}l_{ji}y_i \quad (12)$$

where the first term, $c_i[(1 - a_{ii})^{-1} - 1]y_i$ shows the emissions generated in the own production of sector i through its internal inputs. The second term, $c_i(1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij}l_{ji}y_i$ shows the emissions from sector i required for the production of inputs that it demands from other sectors, that is, the growth of emissions of sector i when an additional unit of final demand in sector i increases via sector j .

The total emissions associated with the components of sector i can be determined as:

$$\begin{aligned} e'_i &= c_i[(1 - a_{ii})^{-1} - 1]y_i + c_i(1 - a_{ii})^{-1} \sum_{i \neq j} a_{ij}l_{ji}y_i + \sum_{i \neq j} c_jl_{ji}y_i + c_iy_i \\ &= INT_j + FEB_j + SPI_j + DIR_j \end{aligned} \quad (13)$$

This final expression allows for the analysis of the emissions of each sector according to its relationship with the other sectors of the economy. The total emissions of sector i is decomposed into four components: internal component (INT), feedback component (FEB), spillover component (SPI) and direct component (DIR). The internal, feedback, and direct components maps all carbon emissions from production of sector i ; these terms sum to total own emissions. The inter-sectoral transfer of embodied CO₂ emissions in the supply chain can then be determined based on sectoral spillover and feedback effects of carbon emissions.

2.2. Data

This paper utilizes Chinese input-output tables for 1997 (40 sub-sectors), 2002 (42 sub-sectors), 2007 (42 sub-sectors), and 2012 (42 sub-sectors) (NBS, 1999, 2006, 2009, 2015). The tables were harmonized across the years by aggregating to 26 sub-sectors (these sub-sectors are described in Table 1). For ease of analysis, we first perform all calculations at the level of 26 sectors, and then aggregate results to 9 sectors in which sub-sectors are included. Thus, the entire China economy was divided into 9 broader sectors: agriculture, mining, heavy manufacturing, light manufacturing, equipment manufacturing, power, construction, transportation, and services. Energy use in China was obtained from the final energy consumption data of China Energy Statistical Yearbooks (NBS, 1998, 2003, 2008, 2013). National Bureau of Statistics of China provides competitive I-O tables, however, the non-competitive I-O table has the advantage of giving more precise estimates of emissions considering domestic production technology matrix (United Nations, 1993; Su and Ang, 2013). Thus, in contrast to the previous measurement based on competitive I-O tables, the calculation in this paper is based on Chinese non-competitive import I-O tables.

Table 1. Sectors classification for the Chinese economy.

Sector	Code	Sub-sector
Agriculture	AGR	Agriculture

Mining	MC	Mining and Washing of Coal
	MPN	Extraction of Petroleum and Natural Gas
	MM	Mining and Processing of Metal Ores
	MO	Mining of Other Ores
Heavy manufacturing	PC	Petroleum Refining and Coking
	CHE	Chemical
	NMP	Non-metallic Mineral Products
	SPM	Smelting and Pressing of Metals
Light manufacturing	FD	Food
	TEX	Textile
	TR	Textile Related Products
	TF	Processing of Timber and Furniture
	PP	Paper and Paper Products
	OM	Other Manufacturing
Equipment manufacturing	MP	Metal Products
	GE	General Equipment
	TE	Transport Equipment
	EME	Electric Machinery and Equipment
	EE	Electronic Equipment
	IM	Instruments and Machinery of Cultural Activity and Office Work
Power	POW	Power
Construction	CON	Construction
Transportation	TRA	Transportation
Services	WRC	Wholesale, Retail Trade and Catering Service
	OS	Other Service

We use 16 kinds of fossil fuels for the economic sector to estimate carbon emissions, including: raw coal, cleaned coal, other washed coal, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquid petroleum gas, refinery gas, other petroleum products and natural gas. We refer to Zhang et al. (2015)'s method to estimate sectoral CO₂ emissions, in which the emissions from fuel combustion equals to the final use of energy plus energy inputs or losses during energy transformation processes. Therefore, energy inputs embodied in the transformation of thermal power and heating supply are allocated to energy consumption in the power sector. The net calorific value and CO₂ emission factor of the various fuels are listed in Table A1 of Appendix A.

3. Results

First, we present the general trends and sectoral contributions under the demand-induced accounting principle as compared with the output-induced accounting principle. Then we decompose the total sectoral emissions into the four components; internal, direct, feedback, and spillover. Finally, we analyze the evolution of inter-sectoral linkages in China's demand-induced carbon emissions by analyzing the ranking of spillover and feedback emission shares among 26 sub-sectors.

3.1. General trends and sectoral contribution

In the 15 years from 1997 to 2012, China's emissions rose 160%, from 3118 to 8090 million tons (Mt) (see Fig.1). After 2002, China experienced a quick increase in total CO₂ emissions. Growth in emissions were, on average, 17.2% per year during 2002-2007, decreasing to 5.9% per year during 2007-2012. These trends mirror the evolution of the

Chinese economy during this time period: growth of the Chinese economy accelerated, reaching an average GDP growth of over 10% per year between 2002 and 2007 (NBS, 2008). The high rate of economic growth led to a rise in carbon emissions as fast economic development provided consumers with more disposable income driving goods and services consumption, including energy. The emission growth rate dropped to 5.9% in 2012, largely due to the effects of the 2008-2009 global economic crisis, and an overall fall in final demand. Before moving to sectoral results we validate our total emission calculations against those from the Energy Information Administration (EIA, <http://www.eia.gov/>), Emission Database for Global Atmospheric Research (EDGAR, <http://edgar.jrc.ec.europa.eu/>), British Petroleum (BP, 2014), Carbon Dioxide Information Analysis Centre (CDICA, <http://cdiac.ornl.gov/>), and Liu et al (2015b). These estimates vary as to the types of gas and processes that are included (see Fig 1). Methodologically, our results are most similar to Liu et al (2015b) because, like them, we estimate CO₂ emissions only, and do not include CH₄ and N₂O. Liu et al., (2015b) presented revised estimates of Chinese CO₂ emissions using two sets of new measurements of emission factors and find a revised estimate of CO₂ which is lower than estimates from other inventories. Our estimate of total emissions is still 9% lower than those of Liu et al., (2015b) in 2012. This is because we do not estimate emissions embodied in industrial processes, and cement process emissions accounted for about 9% of China's total CO₂ emissions over this period (Liu et al., 2015b).

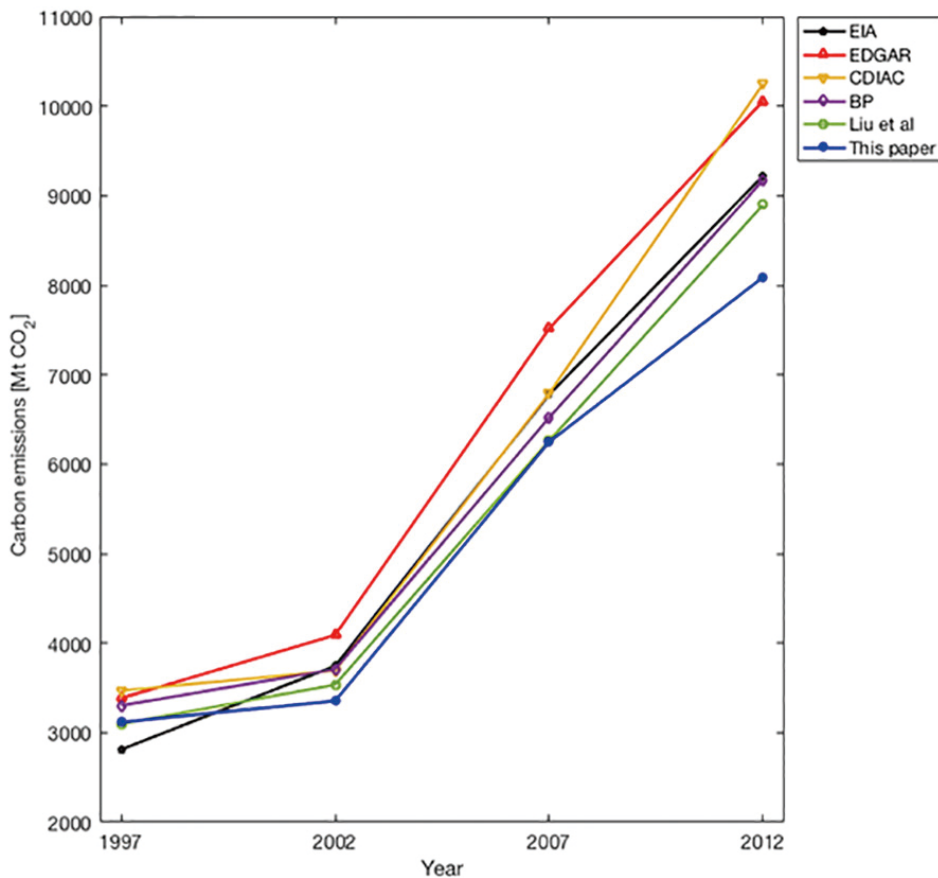


Fig.1. The general trends of carbon emission from 1997 to 2012 based on different estimations.

As illustrated in Fig. 2 the carbon emissions of 1997 and 2012 show significant changes in the ranking of demand-induced carbon emissions among the 26 sub-sectors when compared to output-induced emissions. The output-induced emissions of power sector were largest, accounting for 40.1% and 49.3% of the total in 1997 and 2012 respectively. The second largest emitter was heavy manufacturing sector with 35.1% in 1997 and 32.5% in 2012. Comparing with output-induced accounting shows that the construction sector was the largest demand-induced emitter, and equipment manufacturing ranked second.

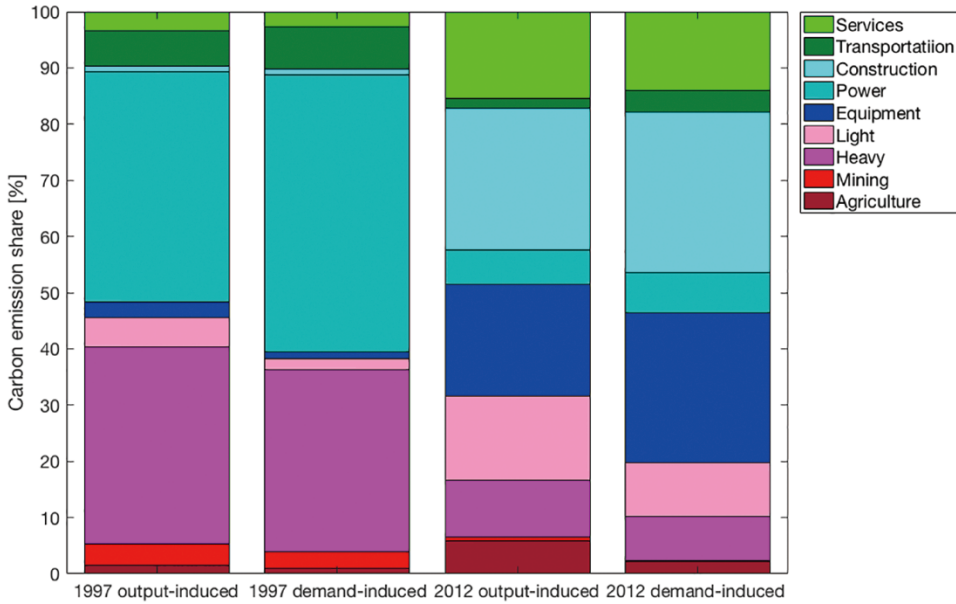


Fig.2. Carbon emission share under the output-induced and demand-induced principles (1997 and 2012).

Table 2 shows the significant changes over 1997-2012 in the emission shares of sub-sectors in the total emissions of China under demand-induced principle. The construction sector is a key emitter through all years, peaking at 28% of emissions in 2012. Emissions in equipment manufacturing sub-sectors grew quickly from 1997 to 2012. For example, general equipment grew from 6.5% in 1997 steadily to 8.6% of all emissions by 2012. This trend is repeated in the transport equipment sub-sector, growing from 3.7% to 6.6% by 2012. Other notable trends are the reduction in contributions from primary sectors such as agriculture (dropping 5.8% to 2.1% by 2012), along with some light manufacturing sub-sectors such as the food (FD). In 1997, the transportation sector accounted for around 1.8% of emissions, with an absolute increment of 255 Mt in 2012. Other sectors such as the power sector show a consistent proportion over time. We note that demand-induced emissions in the mining sector present a decreasing trend, which can be explained by reductions in emission coefficients and the slow growth of final demand. We take Mining and Washing of Coal (MC) sub-sector as an example, CO₂ emissions per unit of economic output decreased from 1.04 tons in 2002 to 0.67 tons in 2012 due to technological improvement. Furthermore, the final demand for coal grew slowly between 2002 and 2012 due to an export reduction of 0.7 million yuan (NBS, 2013) and a great decrease in household consumption caused by a ban on the burning of coal for domestic heating in cities.

Table 2. Contributions of demand-induced emissions in sub-sectors from 1997 to 2012.

Sub-Sectors	1997		2002		2007		2012	
	Mt CO ₂	%	Mt CO ₂	%	Mt CO ₂	%	Mt CO ₂	%
AGR	180.52	5.79	161.63	4.82	131.38	2.10	169.44	2.09
MC	9.73	0.31	18.16	0.54	12.44	0.20	10.11	0.12

MPN	9.14	0.29	5.11	0.15	5.51	0.09	7.17	0.09
MM	1.34	0.04	1.48	0.04	6.79	0.11	2.32	0.03
MO	4.58	0.15	4.98	0.15	3.73	0.06	0.92	0.01
PC	20.73	0.66	15.55	0.46	36.32	0.58	54.74	0.68
CHE	184.33	5.91	155.92	4.65	298.57	4.78	336.16	4.16
NMP	87.93	2.82	54.51	1.62	76.56	1.23	98.63	1.22
SPM	20.00	0.64	30.66	0.91	254.46	4.07	149.64	1.85
FD	198.76	6.37	138.19	4.12	224.25	3.59	304.58	3.76
TEX	71.55	2.29	78.54	2.34	154.03	2.47	70.13	0.87
TR	97.62	3.13	83.98	2.50	152.10	2.43	193.05	2.39
TF	27.54	0.88	25.82	0.77	70.81	1.13	75.86	0.94
PP	40.96	1.31	34.62	1.03	53.94	0.86	116.95	1.45
OM	29.27	0.94	20.26	0.60	45.17	0.72	9.11	0.11
MP	84.07	2.70	70.51	2.10	153.30	2.45	172.61	2.13
GE	203.27	6.52	223.05	6.65	501.31	8.02	696.11	8.60
TE	115.44	3.70	105.82	3.15	301.65	4.83	532.70	6.58
EME	120.60	3.87	103.28	3.08	318.34	5.10	397.61	4.91
EE	82.33	2.64	143.66	4.28	319.45	5.11	328.60	4.06
IM	16.79	0.54	36.72	1.09	61.07	0.98	32.71	0.40
POW	190.50	6.11	295.16	8.80	428.79	6.86	577.01	7.13
CON	784.76	25.17	796.23	23.73	1533.36	24.54	2308.11	28.53
TRA	57.38	1.84	128.07	3.82	257.05	4.11	311.85	3.85
WRC	100.16	3.21	146.17	4.36	204.81	3.28	201.96	2.50
OS	378.79	12.15	477.52	14.23	642.94	10.29	932.17	11.52
Total	3118	100	3356	100	6248	100	8090	100

3.2. The decomposition of sectoral emissions

For ease of explanation, we aggregate results of 26 sector to 9 major sectors, and then report the results of each sector separately. Fig.3 presents the decomposition of total emissions into internal, feedback, spillover, and direct components for the sectors outlined in Table 1. Fig.4-7 show the disaggregate-level analysis for sectors with many sub-sectors.

Agricultural emissions were driven by spillover effects, accounting for 81.0% of total agricultural emissions by 2012. Agricultural emissions in the direct component grew rapidly from 11.4% in 1997 to 24.6% by 2007, before dropping significantly to 15.5 % by 2012. These reductions reflected a shift from traditional agricultural activities to industrial activities. The proportion of the internal component increased from 2.1% in 1997 to 3.8% in 2010, then decreased to 2.3%. Given projected increases in Chinese population, direct demand will continue to increase carbon emissions in the agriculture sector, but spillover effects from agricultural demand are now a dominant issue.

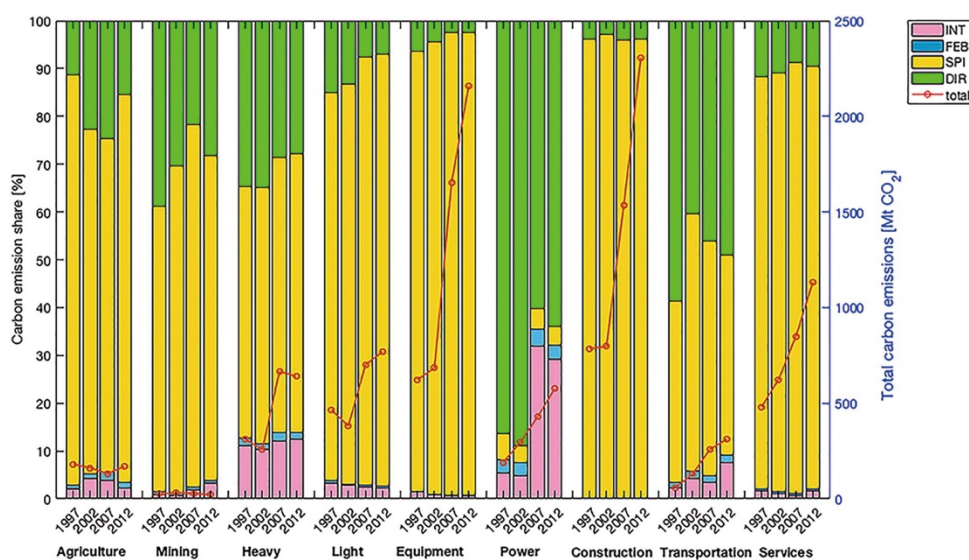


Fig.3. Decomposition of demand-induced emissions from 1997 to 2012.

In the mining sector, the spillover component was important over the period, and by 2012 was 68.0% of the total. The direct component was another major contribution, and by 2012 was 28.1% of the total. The internal component increased from 0.8% of the total in 1997 to 3.2% by 2012. The feedback component shows a stable share over time. Within the mining sector, the Mining and Washing of Coal (MC) sub-sector is the most active sub-sector, resulting from high levels of final demand (see Fig.4). The emissions of the direct component accounted for above 30% of total emissions in the MC sub-sector from 1997 to 2012. The share of direct component in the MC sub-sector has fluctuated greatly with the share decreasing by 8% from 1997 to 2002. This is mainly due to increased intermediate inputs in the production processes of MC sub-sector, resulting in the growth of the spillover effect. While the spillover effect decreased by 12%, the share of the direct component increased by 6% from 2002 to 2012. Extraction of Petroleum and Natural Gas (MPN) is the second largest contributor to CO₂ emissions in the mining sector, which is driven by the fact that China is now one of the most important producers of petroleum and natural gas in the world. From 1997 to 2007, emissions in MPN decreased nearly 44%. This can be explained by the drop in international oil prices which shrank total production. After 2002, MPN sub-sector grew at a slow pace as the economy expanded, representing an annual 4.1% increase. From 2002 to 2007, Mining and Processing of Metal Ores (MM) sub-sector grew 4 times, in step with increased demand due to the takeoff of the Chinese economy, particularly in infrastructure and manufacturing. The slowdown in economic

growth in 2012 has caused little economic incentive to increase CO₂ emissions in MM sub-sector. Similar trends occur in the Mining of Other Ores (MO) sub-sector.

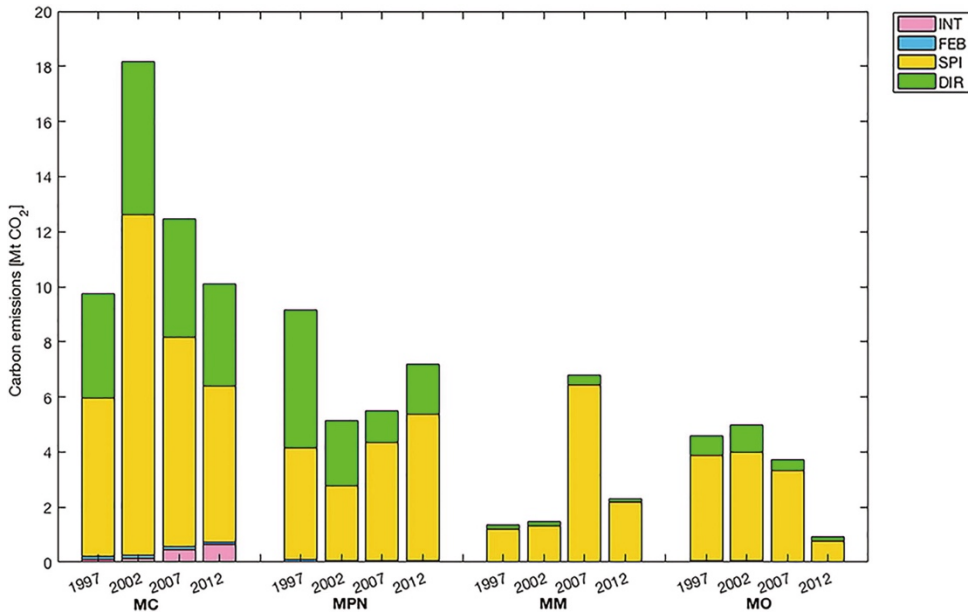


Fig.4. Decomposition of demand-induced emissions in the mining sector from 1997 to 2012.

Emissions in the heavy manufacturing sector grew 131%, from 257 Mt in 2002 to 666 Mt in 2007. In 2012, as the sector reaches maturity, we observe a small reduction in emissions which may be driven by government policies aimed at adjusting the Chinese economic structure. This is exemplified by the shifting of China's economic growth model from industry to services, which decreases the share of the heavy manufacturing sectors in China's value added output, and increases the proportion of labor and technology-intensive sectors. In the heavy manufacturing sector, the spillover component is a key factor, accounting for 58.5% of the total in 2012. 374 Mt CO₂ emissions in other sectors were driven by the final demand for heavy manufacturing sector. Energy-intensive supply chains, related to the production of non-ferrous metals, chemical manufacturing, and metal products, may explain the largest effect of spillover component. Emissions in 1997 in the internal component comprise 11.1% of the total, and its share experienced a slight increase in the total carbon emissions (to 12.4% in 2012). Turning to the feedback share, the proportion grew gradually and eventually stabilized from 2007-2012 to 1.4% of the total. We present further sectoral decomposition results in Fig.5. In 1997, the chemical emissions were dominated by spillover effects, accounting for 53.7% of the total. The spillover effect of the chemical sector showed a sharp upward trend between 1997 and 2007, with its share in 2007 accounting for 67.3% of the total emissions. In 2012, the spillover emission share fell slightly from 67.3% to 65.8%, while the internal component increased to 12.8%. Smelting and Pressing of Metals (SPM) had a rapid increase in the emissions between 1997 and 2007 due to a significant growth of the direct component, before reducing again by 2012. The direct component clearly demonstrates the direct demand effects of CHE and SPM subsectors on carbon emission. With fast economic development, China's chemical and metal consumption has increased rapidly, driven by

massive infrastructure construction. For example, China has become the world's second largest consumer of basic chemical products. In addition, the largest growth in the internal component was from CHE and SPM sub-sectors, with their internal components in 2012 increasing by 17 Mt and 8 Mt, respectively, compared to 1997. This suggests that improvements in the emission efficiency in the production of chemical materials and metal products is limited. Advancements in technology and energy efficiency in the production process has not kept pace, resulting in much higher internal proportions than other heavy manufacturing sectors.

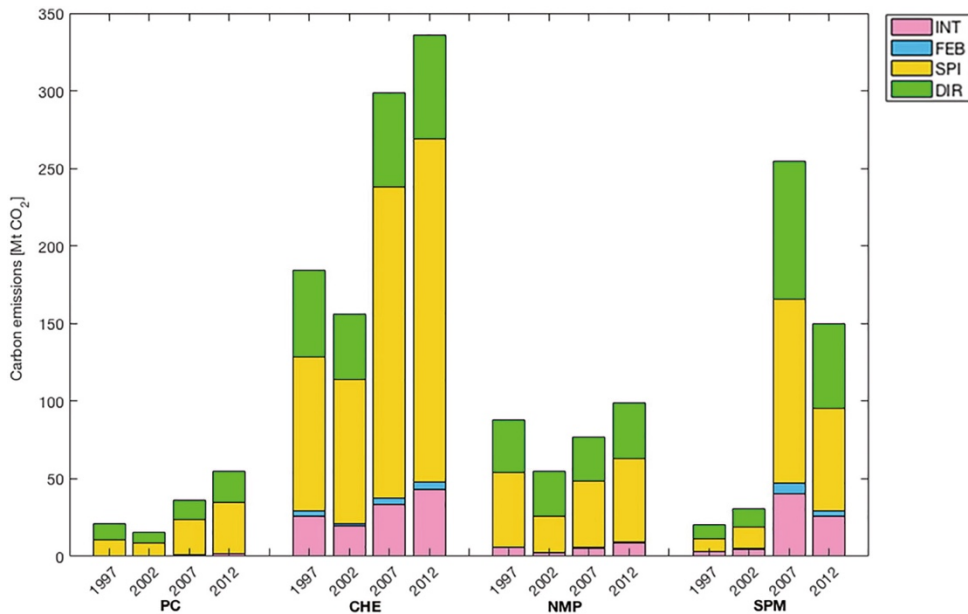


Fig.5. Decomposition of demand-induced emissions in the heavy manufacturing sector from 1997 to 2012.

In the light manufacturing sector, the spillover component was a major driver between 1997 and 2012. The share of spillover emissions increased from 81.1% to 90.4% by 2012 due to the rapid growth of final demand-supporting extensive industrialization. Over the same period, the direct component was the second largest, but did decrease from 15.1% to 7.0% by 2012. The internal effect also shows a significant contribution to total emissions, with the share decreasing from 3.2% to 2.2% by 2012. Fig.6 shows that the largest sub-sector with high spillover emissions was Food (FD). In 2012, the spillover component of FD sub-sector was 86.7% of the total, meaning that 86.7% of the emissions generated by the other sectors are incorporated into the final production of FD sub-sector. Meanwhile, the feedback component in FD sub-sector in 1997 was more than 1% reducing to 0.9% in 2012.

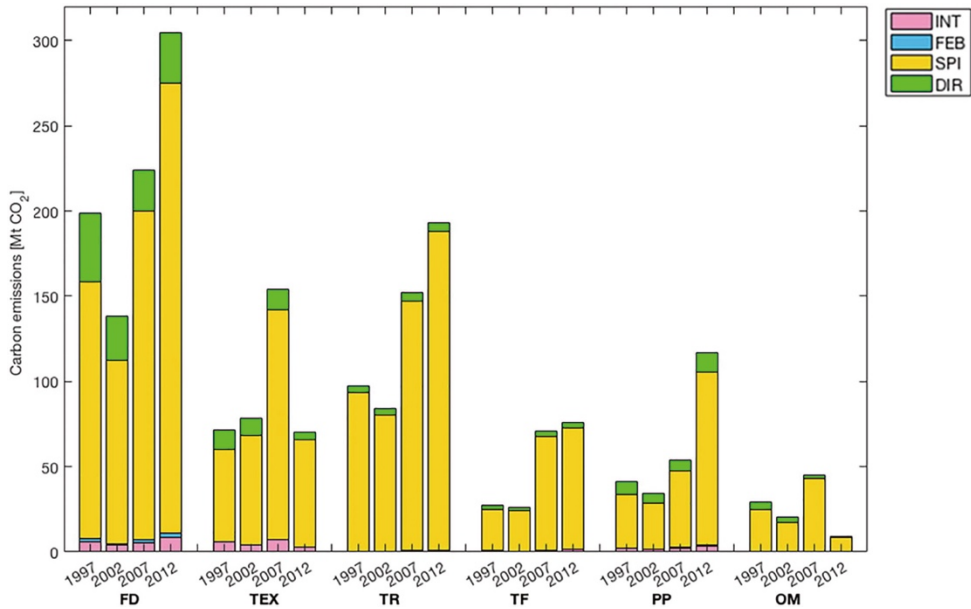


Fig.6. Decomposition of demand-induced emissions in the light manufacturing sector from 1997 to 2012.

From 1997 to 2012, equipment manufacturing emissions increased almost 4-times. Between 1997 and 2002, China had a comparative advantage in light manufacturing sector such as food and beverages, textile, wood, paper. The comparative advantage of this sector declined in the twenty-first century. Equipment manufacturing began to boast a significant comparative advantage after 2002, especially for machinery and transport equipment. By producing and exporting more goods, carbon emissions in equipment manufacturing sector increased rapidly. This increase was dominated by spillover, which increased from 92.2% in 1997 to 96.8% in 2012. The carbon emissions induced by spillover for the equipment manufacturing sector are much higher than other sectors because of its role as processing sector, and the fact that its final product has a long life cycle. Therefore, the growth of its output is dependent on the other sectors and requires plenty of intermediate inputs. During this period, at sub-sectoral level, the General Equipment sub-sector (GE) was the fastest growing sector, followed by Transportation Equipment sub-sector (TE), both of which indicated a fast spillover component growth than industrial average (see Fig.7). For instance, in 1997, 178 Mt and 104 Mt of carbon emissions were emitted in the spillover component in the general and transportation equipment manufacturing sub-sectors respectively. This accounted for 87.6% and 90.2% of the total emissions in these two sub-sectors respectively. By 2012, carbon emissions in the spillover component increased to 661 Mt (94.9% of total) and 511 Mt (96.0% of total) in the general and transportation equipment manufacturing sub-sectors respectively. The share of the spillover component for the Electric Machinery and Equipment (EME) and Electronic Equipment (EE) manufacturing sub-sectors are much larger than those of other equipment manufacturing sub-sectors. In the case of electric and electronic equipment manufacturing in 2012, the spillover effects amounted to 96.8% and 99.1% of the total emissions, respectively. The final demand of these sectors leads to a significant increase in emissions from the production of other sectors.

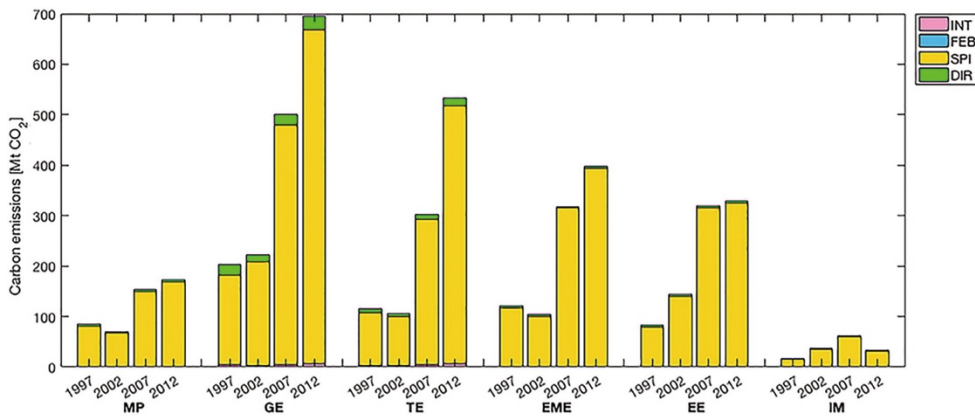


Fig.7. Decomposition of demand-induced emissions in the equipment manufacturing sector from 1997 to 2012.

As shown in Fig.3, the total emissions from the power sector increased rapidly between 1997 and 2007, reaching as much as 577.0 Mt in 2012. The direct component, accounted for over 60% of the total emissions induced by the final demand of the power sector between 1997 and 2012. Emissions in the direct component increased from 164.6 Mt to 257.8 Mt in 2007 due to a rapid growth of electricity consumption by China's urban households. The total electricity consumption by China's urban households increased at an annual average rate of 10% between 1997 and 2007 (Akinobu et al., 2008). The internal component was another major contributor to total emissions, which was stable as a proportion, at around 5.5% and 4.8% in this early period, then increased dramatically from 4.8% in 2002 to 32.0% in 2007 before reducing again by 2012. This is because the share of input from its own sector in the total input (a_{ii}) increased to 0.35 in 2007 from 0.06 in 1997 (NBS, 1998, 2008). If we take into account the fact that the spillover component of power sector emissions amounted to 23.4 Mt in the year 2012, then only 4.1% of emissions generated by other sectors were incorporated in the emission in power sector. This is likely due to the fact that the power sector is the primary provider of secondary energy carriers (electricity) for other sectors, and thus the power sector is dependent on the development of those sectors.

In the construction sector, emissions have risen significantly, with relatively rapid growth between 2002 and 2012, driven by uniform, rapid growth of final demand. This is predominantly driven by urbanization, industrialization, rising personal income levels, further population growth, and household growth driving a housing boom. The main source of carbon emissions in the construction sector depends, to a greater extent, on the spillover component from 1997 to 2012. This means that the construction sector has a strong pulling effect on the carbon emissions generated in the production processes of the rest of the economy. For example, the iron and steel sector is closely related to the construction sector. The construction sector has the potential to contribute to the output of iron and steel and to the growth of the carbon emissions in the production processes of iron and steel sector. The spillover component dominated in the early years and increased

further, from 96.1% in 1997 to 97.1% in 2002. The direct component was also an important driver in the increase of emissions in the construction sector, with a share in the total emissions of 3.9% in 1997. In 2012, the spillover component and direct component contributed to 96.1% and 3.8% of the emissions in the construction sector, respectively, while the total emissions grew almost 3 times.

In transportation, emissions grew rapidly to 311 Mt by 2012, with direct component as a major driver, since transportation is one of the main human activities in China. Nevertheless, there was obvious reduction tendency for the growth rate of total carbon emissions from 1997 to 2012, and the 21.3% emission growth between 2007 and 2012 was the lowest growth rate since 1997. This can be largely explained by changing consumer attitudes and macroeconomic headwinds. In 2012, the direct component of transportation sector was 153 Mt (48.9%) higher than other components. The improved living standards of residents have stimulated both the demand for private cars and tourism, and thus carbon emissions in the direct component were four-times the amount of those of 1997. The spillover component was another primary factor from 1997 to 2012, peaking at 53.9% of emissions in 2002. This suggests that the transportation sector's emissions still have a great dependence on intermediate inputs from other sectors, since the sector consumes a large amount of energy-intensive materials and resource-consuming products from other sectors.

Emissions from the services sector also grew rapidly over the entire period, from 479 Mt to 1134 Mt, with spillovers growing rapidly, accounting for 88.3% of total emissions by 2012. Most service emissions are upstream, occurring in material and energy production sectors due to the link between services and manufacturing. For instance, manufacturing creates products for much of the retail trade. From a direct component perspective, emissions from services grew from 56 Mt in 1997 to 68 Mt in 2002. Afterwards, emissions from the direct component increased at an annual rate between 1.8% and 9.3%. While the direct component's share decreased slowly in recent years, reaching 9.6% in 2012, it remains an important driver in emissions from services. This suggests that, although most services emissions still come from upstream emissions in non-service sectors, focusing on the decarbonization of the services sector directly would be worthwhile.

3.3. Comparisons of spillover and feedback emissions

The feedback and spillover effects outlined above provide a new method of studying inter-sectoral economic relationships and influences, but the results above show the share of feedback effects in the total sectoral emissions is small. Therefore, we further analyze the shares of the feedback and spillover components for different economic sectors.

Fig.8 reflects feedback and spillover shares among the 26 sub-sectors in 1997 and 2012. Fig.8 also presents the absolute emissions of feedback/spillover components in 1997 and 2012, which are similar to the results of feedback/spillover shares. This allows us to identify which sub-sectors have the higher feedback/spillover shares. In 1997, the feedback effect share in the Power (POW) sub-sector was significantly higher than that of other sub-sectors, with 2.7%. The second largest feedback share was in Smelting and Pressing of Metals (SPM), at 2.5%. The following five largest feedback shares were in Chemical (CHE), Transportation (TRA), and Food (FD) sub-sectors, ranging from 1.1 to 1.9 %. In 2012, POW and SPM were the only two sub-sectors with feedback shares above 2%. Feedback in the agricultural sector grew the most from 1997 to 2012, approximately

doubling in size. The feedback share in the transportation sector is also high, at 1.5%. This means that agriculture and transportation had a much closer relationship with other sectors. The feedback component shares of heavy manufacturing sub-sectors are relatively high compared to those of other sub-sectors, ranging from 0.5 to 2.1 %. This implies that other sectors' output has important effects on carbon emissions from the production activities of heavy manufacturing. The feedback share of Mining and Washing of Coal (MC) presented a stable increasing trend from 0.7% in 1997 to 1.2% in 2012. During this period the feedback component in the food sub-sector decreased from 1.1% in 1997 to 0.9% in 2012.

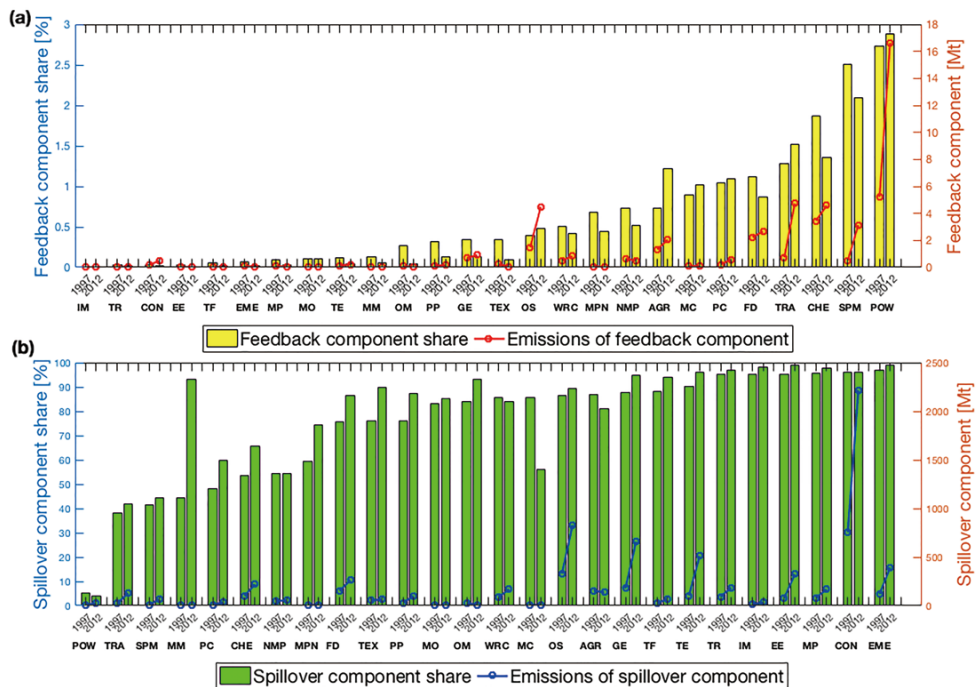


Fig.8. Comparison of spillover and feedback emission share for different sub-sectors (1997 and 2012).

The ranking of the spillover component reflects that, in 1997, the share of spillover emissions in the Electric Machinery and Equipment (EME) sub-sector was the largest, accounting for 96.8% of the total emissions in the EME sub-sector. The remaining sectors in the top five were in Construction (CON), Mental Products (MP), Electronic Equipment (EE), and Instruments and Machinery of Cultural Activity and Office Work (IM). In addition, most sectors with a higher spillover share have a lower feedback share. For example, the feedback shares in the EME and CON sub-sectors were significantly lower than those of other sub-sectors, accounting for 0.07% and 0.03 % of the total, respectively. In 2012, the spillover effect share of Electric Machinery and Equipment (EME) remained the largest, with the Electronic Equipment (EE) sub-sector ranked second. The following four largest spillover effect shares were in Instruments and Machinery of Cultural

Activity and Office Work (IM), Metal Products (MP), Textile Related Products (TR), and Construction (CON) with shares ranging from 99.1% to 96.1%. This means that the equipment manufacturing and construction sectors have caused large amounts of spill over emissions to other sectors. We note that more than 45% of the emissions in the heavy manufacturing sector are discharged in other sectors in 1997 and 2012, but their shares of spillover component are much smaller than those of other sectors.

3.4. The distribution of spillover emissions

Since spillover effects capture emissions embodied in the intermediate inputs of other sectors, these effects can reflect inter-sectoral embodied emission transfers, and describe how a sector's final demand affects CO₂ emissions in other sectors. We pick out light manufacturing, equipment manufacturing, construction, and services sectors (spillover shares are more than 80% during the whole studying period) to further analyze the distribution of spillover effects in the supply chain. For sectors with many sub-sectors, we choose a sub-sector with the largest demand-induced emissions as an example, thus, Food (FD), General Equipment (GE), and Other Services (OS) sub-sectors are considered. As final demand is considered as the driving force for emissions emitted in supply chains, we also identify how different final demand categories (rural household consumption, urban household consumption, government consumption, investment and exports) cause spillover effects. We incorporate government consumption into urban household consumption as this amount is small and structurally consistent (that is both categories are consumptive). Fig.9 shows the five most important destinations of spillover effects for each selected sector in 1997 and 2012.

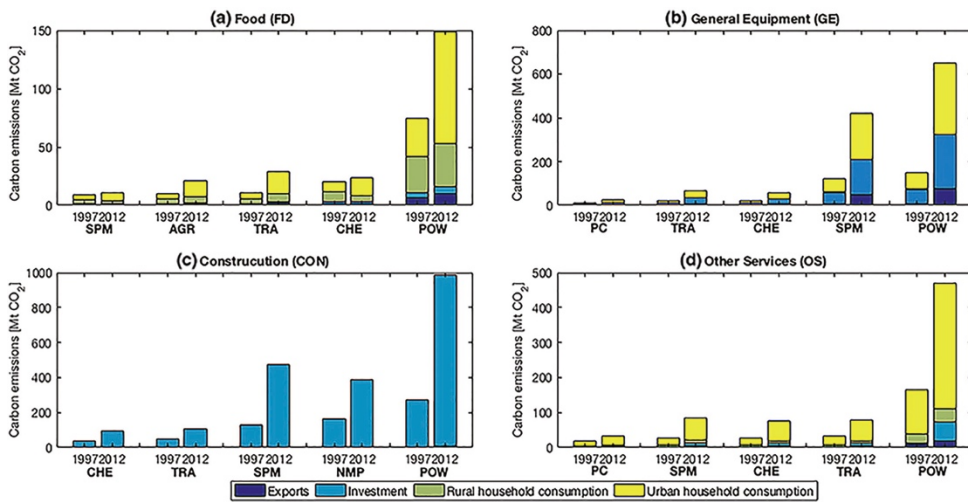


Fig.9. The most important destinations of spillover emissions for sectors of food (a) general equipment (b) construction (c), other services (d) (1997 and 2012).

The distribution of spillover effects for food, general equipment, construction, other services sectors mainly concentrate on power, transportation and heavy manufacturing sectors. The final demand of the food sub-sector in 1997 drove 10 Mt CO₂ of emissions in the agriculture sector, increasing to 21 Mt by 2012. This can be explained by increased household consumption. In 1997, spillover effects of the food sub-sector were driven by rural household consumption (41.3%), while in 2012, spillover was dominated by urban

household consumption (64.5%). This is unsurprising given accelerated urbanization, leading to expansion of the food sub-sector and its CO₂ intensive supply chain. The rapid growth of emissions in the Smelting and Pressing of Metal (SPM) and power sectors from 1997 to 2012 were driven by capital investments in the general equipment and construction sectors. This is because China became a member of the World Trade Organization in 2001, which not only provided a more favorable environment for foreign investment in China, but also brought opportunities for both domestic and foreign companies to start contracting construction businesses. As a result, the final demand of equipment and construction sectors grew, and spillover effects increase simultaneously. Moreover, China's housing boom presented opportunities for investors in the construction sector, which led to an increase in the scale of construction, and growth of emissions. In 1997, the final demand of the Other Services (OS) sub-sector led to 166 Mt CO₂ in the power sector, then rapidly increased to 360 Mt in 2012. CO₂ emissions in the transportation sector induced by the Other Services (OS) sub-sector showed a 59 Mt growth, reaching 86 Mt in 2012. Urban household consumption played an important role in increasing the spillover effect of the Other Services (OS) sub-sector, accounting more than 70% of the total. The spillover emissions induced by services investment grew 10% from 1997 to 2012, as the economic structure was rebalanced from manufacturing to services. It is noteworthy that Fig.9 shows little demand changes from exports. This contrasts with the results of Ou et al., (2017) and Huo et al., (2014) who identified exports as a major driver of China's carbon emissions. However, it should be noted that the sector with the largest contribution to total CO₂ emissions embodied in exports is the heavy manufacturing sector (Tang and Lin, 2017), which is not represented in Fig.9. The sectors represented in Fig.9 contribute little to total CO₂ emissions embodied in exports. Thus, the apparent conflict between our results and those found in the literature is explained by a different sectoral focus.

4. Discussion

Above, we report the results of our analysis, showing that, the relative importance of different components depends on the position of each sector in the supply chain. The direct, internal and feedback components reflect the CO₂ emissions produced in the production processes of sectors. The contribution of the three components for power sector is relatively larger, as it is not surprising that the electricity and fossil fuel are the top emitting sectors. The spillover component indicates the pulling effect of demand of a sector on CO₂ emissions produced in the rest of the economy. The contribution of spillover component is mainly responsible for the CO₂ emissions from construction and services sectors. In addition, the most important destinations of spillover emissions for construction and services sectors include heavy manufacturing, power and transportation sectors, as downstream sectors (e.g. services) have a considerable demand for the energy and raw materials of upstream sectors (e.g. power). Those mean that the embodied CO₂ emissions are mainly transferred from the basic industrial sectors to construction and services sectors via inter-sectoral trade.

When considering the relative role of feedback component relative to the spillover component, the share of feedback component for the power sector is the largest, followed by heavy manufacturing and transportation sectors. This means that, upstream sectors gain considerable feedback CO₂ emissions while lots of CO₂ emissions transfer to other sectors. Additionally, heterogeneous sectors, such as the agriculture sector including both

crop and animal production sectors, have relatively high shares of feedback effects than more narrowly defined sectors (e.g. Non-metallic Mineral Products sub-sector).

Our analysis also shows that, during the period 1997-2012, the spillover share of agriculture is higher than 70%, and the spillover share of heavy manufacturing is around 50%. We now turn to specific phenomena within the results and attempt to explain them more generally.

Our estimates for agricultural emissions may not exactly agree with those from the IPCC as those estimates include other GHG types such as CH₄ and N₂O. Although we do not report emissions from agricultural production process, we still obtain meaningful results from the view of inter-sectoral linkage. As shown in Table 3, the agricultural supply chain mainly induces indirect CO₂ emissions in power, transpiration and chemical sectors. In 1997, the agricultural final demand resulted in 75 Mt CO₂ emissions emitted from the power sector via inter-sectoral linkage, accounting for 41.3% of the total agricultural emissions. The emissions in the chemical sector induced by the agricultural demand were 31 Mt, accounting for 17.1% of the total. The agricultural demand caused 10 Mt emissions in the transportation sector, which contributed 5.6% of the total. In 2012, the CO₂ emissions in the chemical, transportation and power sectors induced by the agricultural demand increased to 21 Mt, 10 Mt and 83 Mt respectively due to the doubling of agricultural demand from 2007 to 2012 (NBS, 2008, 2013), while we find a 10 Mt reduction of agricultural direct emissions (as shown in Fig.3) during the same period due to the decreased agricultural emission coefficient. The difference between spillover and direct components highlights that, while the agricultural productivity has been improved in the recent years, low-carbon agricultural supply chains are important to emission reductions.

Table 3. Destinations of agricultural spillover emissions from 1997 to 2012.

Sub-sectors	1997	2002	2007	2012
MC	2.78	1.66	1.67	2.85
MPN	2.66	1.99	0.94	1.19
MM	0.20	0.10	0.05	0.08
MO	0.40	0.17	0.12	0.21
PC	7.41	6.09	3.88	5.93
CHE	30.79	15.99	12.64	20.97
NMP	4.05	3.18	1.53	1.65
SPM	8.47	5.36	4.67	5.09
FD	5.28	3.08	2.64	3.45
TEX	0.77	0.15	0.11	0.13
TR	0.03	0.02	0.02	0.02
TF	0.15	0.10	0.05	0.03
PP	1.00	0.59	0.44	0.32
OM	0.62	0.14	0.04	0.03
MP	0.31	0.20	0.09	0.07
GE	1.21	0.40	0.26	0.28

TE	0.37	0.24	0.11	0.08
EME	0.13	0.05	0.03	0.02
EE	0.04	0.02	0.01	0.01
IM	0.02	0.00	0.00	0.01
POW	74.56	67.97	55.19	83.25
CON	0.11	0.05	0.02	0.04
TRA	10.12	6.78	5.88	9.58
WRC	1.48	1.08	0.71	0.90
OS	1.81	1.17	0.64	1.05
Total	136	3	15	67

The spillover share of heavy manufacturing seems like a large number (around 50% during period 1997-2002), as heavy manufacturing requires many intermediate inputs from other sectors to support its own final demand. Taking the chemical sector in 2012 as an example, the emissions in the power sector induced by the chemical demand were 165 Mt, accounting for 49.1% of the total chemical emissions (as shown in Table 4). The chemical demand stimulated 12 Mt CO₂ emissions in the transportation sector, accounting for 3.6% of the total. This is because exports are the primary medium by which the chemical drives other sectors' emissions, resulting in expansion of bulk chemical shipping market and growth of emissions in the transportation sector. The chemical demand also induced 8 Mt in Mining and Washing of Coal (MC), contributing 2.3% of the total, as coal is the raw material for transformation to a range of chemicals in China (Xie et al., 2010). These finding provide further evidence for the view that unlike other upstream sectors (e.g. power), heavy manufacturing and agriculture sectors are two important conversion sectors that can explain shifts from direct to spillover emissions, as they consume lots of energy and resource-consuming products from power and transportation sectors, causing lots of CO₂ emissions to spill over to the other sectors, and at the same time, they are major input suppliers to the construction and services sectors.

Table 4. Destinations of chemical spillover emissions by different demand categories in 2012.

Sub-sectors	Urban household consumption	Rural household consumption	Capital investment	Export
AGR	0.11	0.51	0.02	1.04
MC	0.52	2.35	0.11	4.77
MPN	0.17	0.77	0.04	1.56
MM	0.01	0.07	0.00	0.13
MO	0.05	0.22	0.01	0.46
PC	0.74	3.34	0.16	6.76
NMP	0.26	1.16	0.05	2.36
SPM	0.74	3.31	0.16	6.71
FD	0.06	0.28	0.01	0.56
TEX	0.03	0.14	0.01	0.28
TR	0.00	0.01	0.00	0.02

TF	0.00	0.02	0.00	0.03
PP	0.04	0.17	0.01	0.34
OM	0.00	0.02	0.00	0.04
MP	0.01	0.04	0.00	0.09
GE	0.02	0.11	0.00	0.21
TE	0.01	0.02	0.00	0.05
EME	0.00	0.01	0.00	0.02
EE	0.00	0.00	0.00	0.01
IM	0.00	0.00	0.00	0.01
POW	11.13	50.08	2.36	101.53
CON	0.00	0.02	0.00	0.04
TRA	0.82	3.70	0.17	7.49
WRC	0.07	0.32	0.02	0.65
OS	0.10	0.43	0.02	0.87
Total	15	67	3	136

5. Conclusions and policy implications

Even though existing studies analyzed some aspects of multi-sectoral carbon emissions in China, to our knowledge, none have analyzed multi-sectoral emissions from the perspective of inter-sectoral production networks including spillover and feedback effect emissions. We comprehensively identify the characteristics and patterns of sectoral emissions in China using an extended subsystem, IO-based, time-series decomposition.

Our results show that, equipment manufacturing, construction, and services sectors are the main sources of demand-induced emissions during the period, largely attributed to the spillover effect. Accordingly, these sectors generate carbon emissions primarily through indirect upstream emissions. Power and transportation sectors show a significant contribution of their direct component to their total CO₂ emissions. These findings indicate that the relative importance of spillover and direct emissions depends on the position in the supply chain. Sectors up in the supply chain (e.g. power) have a higher share of direct emissions while sectors at the end of the supply chain have higher spillover emissions (e.g. services). For the heavy manufacturing and relative heterogeneous sectors (e.g. agriculture), the feedback component should be highlighted. Finally, comparing the feedback component share with the spillover component share for each sub-sector in 1997 and 2012, results show that, in general, sectors with a higher spillover share have a lower feedback effect share. During the whole period, the power sector ranks top in the feedback component shares, while the top places for spillover component shares were occupied by equipment manufacturing, construction, and services sectors.

We also come up with the general patterns about a potential shift from direct towards spillover emissions by discussing the distribution and sources of spillover effects by different demand categories. We find that the distribution of spillover primarily influences power, transportation and heavy manufacturing sectors, as these are producers and suppliers of carbon-insensitive commodities. Construction and services sectors have a great demand for the basic industrial sectors (e.g. transportation and power sectors), thus,

the embodied emissions are mainly transferred from basic industrial sectors to construction and services sectors. It should be mentioned that, although agriculture and heavy manufacturing sector spillover effects are much smaller than those of other sectors, they result in substantial CO₂ emissions in the power sector as electricity is a major intermediate input for both sectors.

Based on our empirical analysis, we argue that implementing appropriate mitigation policies for different sectors should consider inter-sectoral production linkages. Since the demand of downstream sectors such as services can induce emissions in heavy manufacturing, transportation, and power sectors, emission mitigation could be realized by developing a more sustainable demand structure. For example, emissions in the heavy manufacturing and power sectors induced by the capital investment of construction sector could be abated by promoting investments in green building technologies, and reducing unsustainable construction activities or unnecessary waste. Furthermore, as emissions in the transportation sector are mainly driven by the urban household consumption of services, policies focused on low-carbon transportation modes could make large impacts. Moreover, it is very important to control energy consumption in the whole supply chain by improving life-cycle management. For example, since the greatest agricultural spillover emissions are in chemical, power and transportation sectors, improving management of agricultural supply chains can provide a major contribution toward emission reductions, such as improving fertilizer use efficiency, reducing electricity consumed per irrigation, and wasting losses in transport. Finally, the results demonstrate that policies to drive the construction of clean production is of strategic importance to reduce chemical CO₂ emissions, such as upgrading coal transformation technologies, improving recycling processes of coal-based chemicals, and promoting chemical sector's electricity conservation.

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Appendix

Table A1. Calorific values and CO₂ emission factors of 16 types of fuels.

Type of fuels	Net calorific value		CO ₂ emission factor	
	value	unit	value	unit
Raw coal	20.91	GJ/t	1.8592	t/t
Cleaned coal	26.34	GJ/t	2.6409	t/t
Other washed coal	8.36	GJ/t	1.6331	t/t
coke	28.44	GJ/t	2.8313	t/t
Coke oven gas	167.26	GJ/10 ⁴ m ³	7.6220	t/10 ⁴ m ³
Other gas	179.81	GJ/10 ⁴ m ³	2.3235	t/10 ⁴ m ³
Other coking products	28.44	GJ/t	3.0052	t/t
Crude oil	41.82	GJ/t	3.0680	t/t
Gasoline	43.07	GJ/t	2.9251	t/t
Kerosene	43.07	GJ/t	3.0334	t/t
Diesel oil	42.65	GJ/t	3.0959	t/t
Fuel oil	41.82	GJ/t	3.1705	t/t
LPG	50.18	GJ/t	3.1013	t/t
Refinery gas	46.00	GJ/t	2.5982	t/t
Other petroleum products	41.82	GJ/t	2.8563	t/t
Natural gas	389.31	GJ/10 ⁴ m ³	21.6219	t/10 ⁴ m ³

Data Source: IPCC (2006), NDRC (2011).

Chapter 3

Impact of non-fossil electricity on the carbon emissions embodied in China's exports

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Submitted to Journal of Cleaner Production on August 2017, accepted with major revisions

Abstract

China is now the world's largest exporter, commanding a share of global trade which grew from less than 2% in 1990 to 13.8% in 2015. This surge coincided with a decrease in the total carbon emissions of many high-income nations, compensated by the embodied carbon emissions imported from China (often termed carbon leakage). Embodied carbon emissions have been particularly high in Chinese exports due to the domination of coal consumption in China's electricity mix. In order to decarbonize China's electricity system, the government of China embarked on a large-scale, national roll-out of non-fossil electricity (NE). However, due to China's significant spatial heterogeneity, NE resources are concentrated in the western region, while most export-embodied emissions originate from the eastern region. Thus, understanding the inter-regional connections of NE impacts may help facilitate China's efforts to reduce emissions embodied in exports. This study builds a hybrid, energy-economic, multi-regional input-output (MRIO) model and compares the observed NE expansion against a counterfactual scenario without NE deployment. The total contribution of NE expansion between 2002 and 2014 is decomposed into three factors: intra-regional, electricity transmission as well as inter-regional supply-chain. Our results show that NE expansion reduced carbon emissions embodied in exports by 203 Mt (million tonnes) in 2007, 243 Mt in 2010 and 259 Mt in 2014. These mitigated emissions accounted for 11.3% in 2007, 14.9% in 2010 and 19.5% in 2014 of the total emissions embodied in exports. The intra-regional effect accounted for approximately 60% of those CO₂ savings during 2007-2014. The effect of electricity transmission accounted for more than 20%, and the remainder of emission reductions resulted from inter-regional economic linkages.

Keywords: CO₂ emissions; non-fossil electricity; multi-regional input-output model; electricity transmission, supply-chain effect

1. Introduction

China has witnessed a sustained growth of exports in the last two decades, with an annual average growth rate of 6% between 1995 and 2014 (Liu et al., 2016b). China saw a significant expansion in exports after entering the World Trade Organization in 2001, growing at more than 20% per annum from 2001 to 2012 (NBS, 2013). In 2015, China became the world's largest exporter (The World Bank, 2013) and accounted for a share of 13.8% of global trade, whereas that share was less than 2% in 1990 (World Trade Organization, 2016). Such large changes in the size of China's exports from 2002 to 2014 also led to large changes in the total export-embodied emissions. Previous studies on embodied emissions have showed that over the last few decades nearly a quarter of CO₂

emissions in China were related to the production of traded goods and services (Peters et al., 2011).

In 2004, the embodied emissions that derived from China and were exported to Japan, the United States, and Russia represented 48%, 44%, 42% of their total import-embodied emissions, respectively (Liu, 2015). Concurrently, developed countries witnessed the decrease or stabilization of domestic carbon emissions (Lin et al., 2014). However, these decreases were compensated by increased emissions embodied in imports from other nations, and from China in particular (Davis et al., 2011). In 2007, the Chinese trade yielded a net export of 2 Gt of CO₂-eq, with 1.6 Gt CO₂-eq going to Europe, and a net-export of over 1 Gt CO₂-eq to the United States (Tukker et al., 2014). China represented the largest exporter to the Mediterranean area, with 197 Mt export-embodied CO₂ emissions in 2012 (Caro et al., 2017).

However, recent data shows that the total emissions in China, for the first time in recent history, were lower in 2015 than the year before (EDGAR, 2016). This recent decline is likely explained by the development of non-fossil electricity (NE), as China has become one of the world's leaders in NE generation (Wu et al., 2016a). The generation of NE increased almost fivefold from 288 TWh in 2002 to 1375 TWh in 2014, as shown in Fig.1. Up until 2006, NE generation increased modestly on a yearly basis, and thereafter it accelerated. This may be attributed to the 2006 Renewable Energy Law (Hua et al., 2016). By 2014, 24.5% of total electricity generation was from NE, compared to 16.7% in 2006. Hydropower dominated the growth, accounting for 15.9% of the total electricity generation in 2002, and 18.9% by 2014. Wind power generation grew approximately 700% per annum between 2006 and 2014. Solar power generation also increased quickly in recent years after the implementation of the 2011 national feed-in tariff (Wang et al., 2016). After four years of rapid growth at an annual growth rate of over 300%, solar power generation reached 23 TWh by 2014, accounting for 0.4% of the total electricity generation. NE development will likely have significant impacts on the carbon emissions embodied in exports. In particular, they may influence the amount of carbon leakage (Weber et al., 2008). In spite of the clear policy relevance, surprisingly little effort has been paid to the analysis of the historical impact of NE development on China's export-embodied CO₂ emissions. The present paper addresses this knowledge gap.

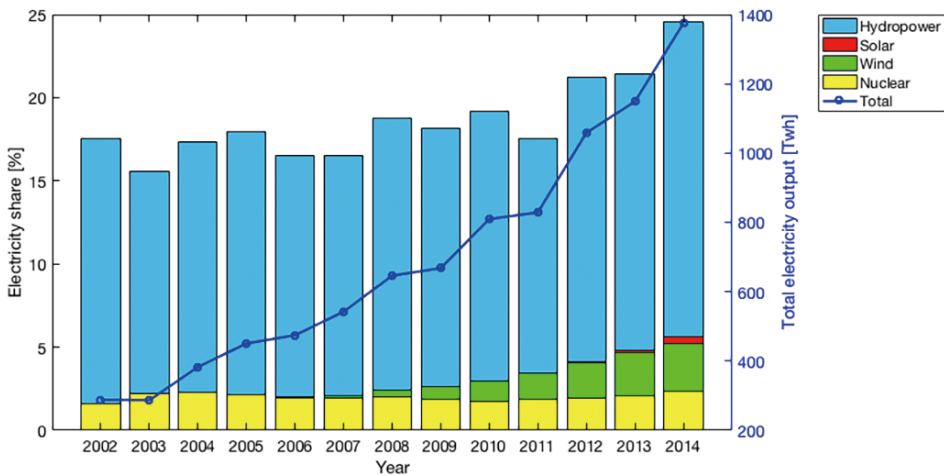


Fig.1. Evolution of shares of different NE types for electricity generation in China (2002-2014).

China is not only a large country, but also regionally diverse. The majority of international exports originate in the eastern, coastal provinces with Shanghai, Jiangsu, Zhejiang, Shandong, and Guangdong, accounting for 74% of China's exports during the period 2002-2014 (NBS, 2015b). At the same time, China demonstrates significant spatial heterogeneity in NE expansion (see Fig.2). In 2002, the southwestern provinces, Qinghai, Sichuan, Yunnan, and Guangxi saw the highest penetration of NE, accounting for over 50% of the total electricity generation. NE generation in the southwestern region also experienced an increase between 2002 and 2014. For example, the share of NE generation in Yunnan increased to 84.3% in 2014 from 61.4% in 2002. In 2014, Qinghai, Hubei, Sichuan, Yunnan, and Guangxi ranked in the top five in terms of the share of NE generation. NE generation in the northern region also experienced a significant growth between 2002 and 2014. For example, the share of NE generation in Inner Mongolia increased from 1.6% to 11.6% with an annual growth rate of 6%. These heterogeneities in both the amount of exports and the endowment of NE resources mean that, in order to assess the impact of NE expansion on China's export-embodied emissions, a spatially-explicit analysis is necessary.

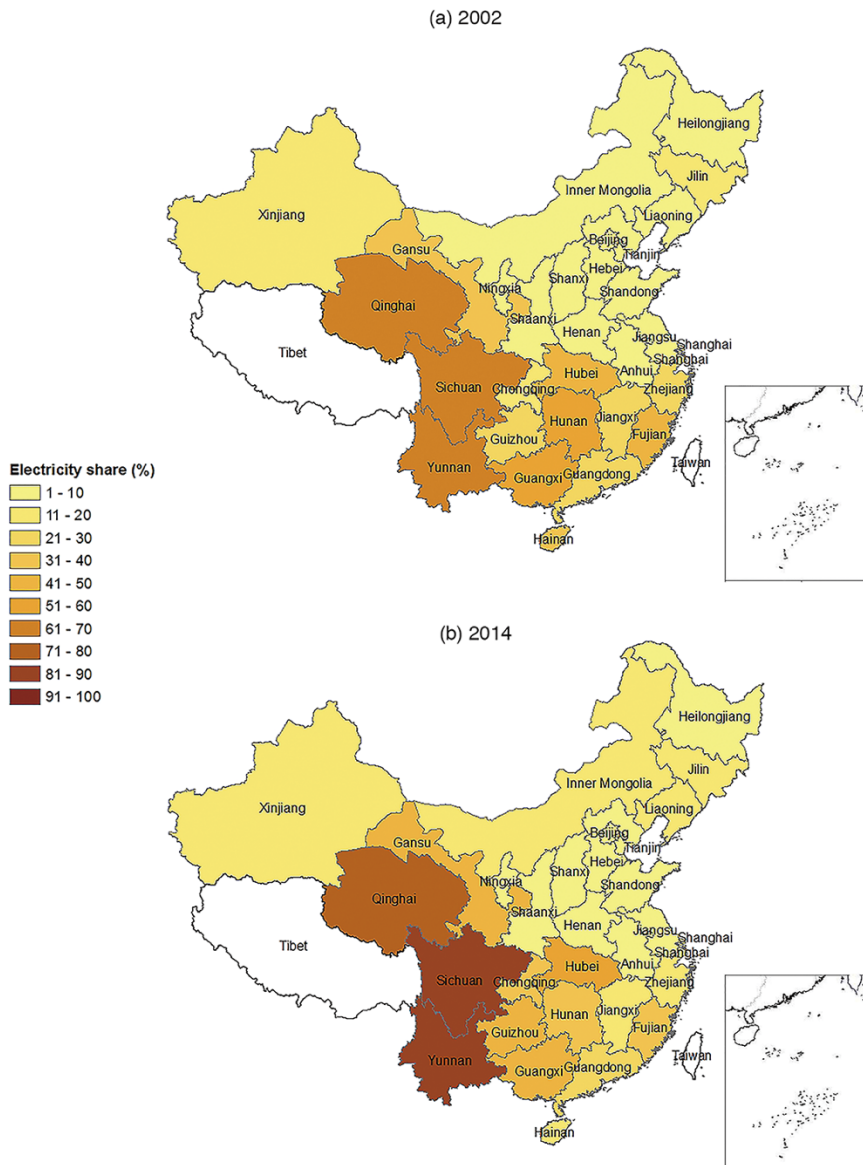


Fig.2. Share of NE in total electricity generation for different provinces (2002 and 2014).

The fundamental question this study wishes to answer is whether the large-scale development of NE during the period 2002-2014 led to a significant reduction of emissions embodied in China's exports. A natural follow-up question is to identify which mechanism is responsible for this behavior. Given the existence of both spatial heterogeneity and economic linkages, this study uses a multi-regional input-output (MRIO)-based model to consider three distinct mechanisms: expansion of the share of NE in intra-regional electricity generation; electricity transmission between provinces,

allowing for NE to be used in different provinces; and supply-chain effect, whereby international exports in a province is assembled from intermediate inputs produced in other regions. This study addresses these questions by comparing the historical carbon emissions embodied in Chinese exports against a counterfactual in which the NE expansion of 2002-2014 did not take place, and the corresponding electricity load is instead generated from fossil fuels. A methodological question that this study has to address is that the most recent, official Chinese MRIO table is from 2010, but large changes in NE generation were observed between 2010 and 2014. As this is an important period, a projected MRIO table for 2014 is built.

In summary, this paper is novel in three key ways. Firstly, this study presents the first-ever analysis of the impact of NE expansion on China's export-embodied carbon emissions, thus clarifying the contribution of China's energy policy to the carbon leakage in international trade. Secondly, this analysis is performed neither for a single year nor for China as a whole, but performed for every province and for several years. This level of detail is important given the dynamic nature of China's economic development, the heterogeneity of China's regions, as well as inter-regional economic and electricity interconnections. Finally, there is a theoretical contribution in this paper to the extent that this study develops a multi-regional economic-energy hybrid model and scenario analysis framework in which the decomposition above could be performed. This model describes the electricity sector in physical terms, thus improving the quality of data.

The rest of the paper is organized as follows: Section 2 summarizes the literature; Section 3 introduces the methods; Section 4 describes the data sources; the results are presented in Section 5; Section 6 presents the conclusions and policy implications.

2. Literature review

2.1. Analysis of environmental impacts of non-fossil fuel electricity development

This study builds upon recent research focusing on the link between NE expansion and the environment. There are several different methods available to evaluate environmental impacts of NE development, including bottom-up energy system models (Li et al., 2012, Budzinske et al., 2017), and top-down energy-economy models (Sonnenschein and Mundaca, 2016). Hybrid approaches combining these methods have also been used (Wolfram et al., 2016). Bottom-up modeling focuses on the energy sector alone, but cannot resolve economic impacts and does not include inter-sectorial/regional feedback effects (Horschig and Thrän, 2017). Top-down modeling focuses on the interaction between the energy sector and the whole economy, and can be used to quantify the impact of energy transition on the rest of the economy (Qi et al., 2014b, Dai et al., 2016). Among top-down approaches, IO models consider the economy as a whole, and are particularly suitable for modeling short-term effects associated with energy technologies (Yushchenko and Patel, 2016). Some IO analyses focus on the environmental impacts associated with future electricity generation technologies (Hienuki, 2015). For example, Song et al., (2015a, b) use IO models and scenario analyses to evaluate the environmental impact arising from future electricity mix in China. Kumar et al., (2016) employ IO models to assess the carbon impact of wind energy farms in the United States. Nagashima et al., (2017) apply IO models to analyze the environmental impact of wind power development in Japan. However, most studies assess the gross environmental impact of

NE development at the national/regional level, and few studies evaluate the impacts of NE expansion on carbon emissions embodied in China's exports.

2.2. IO analysis and China's export-embodied carbon emissions

Given China's dual importance as one of the world's largest CO₂ emitters, and the global leader in trade, IO-based studies on CO₂ emissions embodied in China's trade have been conducted (Qi et al., 2014a, Liu et al., 2016a, Tang et al., 2017, Zhao et al., 2017b). Some researchers use single-region IO models to assess the trend of China's export-embodied emissions, and estimate the drivers of changes in embodied emissions (Weber et al., 2008, Xu et al., 2011, Liu et al., 2017, Tian and Lin., 2017). However, the single-region IO model does not present complex multiple foreign trade links (Xu et al., 2017), and multiregional approaches have been introduced to calculate export-embodied emissions from the perspective of global supply chains (Peters et al., 2011, Deng et al., 2016, Andersson, 2018). Some studies focus on the CO₂ emissions embodied in international trade with specific trading countries, such as the US (Zhao et al., 2016, Zhao et al., 2017a), Japan (Wu et al., 2016b), UK (Li and Hewitt, 2008), and others. These studies show that China is a net exporter of CO₂ emissions embodied in trade with developed countries.

However, given discrepancies in the levels of economic development between provinces in China, the analysis of embodied CO₂ emissions at the national level does not reflect the characteristics of individual regions very well. Also, since emission studies at the national level neglect feedback and spillover effects between regions, the results should be considered approximations (Su and Ang, 2010). Given this, there has been work to use China's MRIO tables in exploring the impact of inter-regional transfer of emissions on China's export-embodied emissions (Feng 2012, Guo et al., 2012, Meng et al., 2013, Weitzela and Ma, 2014, Liu et al, 2015a, Tang et al., 2015, Wang et al., 2015). These studies show that the carbon flows from the central and western regions to the eastern region are the largest contributors to China's export-embodied emissions. Others quantify the driving factors of changes in export-embodied emissions at the regional level in China using decomposition approaches (Zhang and Tang, 2015, Liu et al., 2015b, Mi et al., 2017), and find that low-carbon energy infrastructure may reduce embodied CO₂ emissions. A comparison of results of IO-based studies of China's export-embodied emissions is shown in Table A.1 of Appendix. Note, however, no IO model (or a similar approach) has examined the impact of historical NE development on China's export-embodied emissions with sub-national regional details.

3. Methods

The starting point for this analysis is an environmentally-extended MRIO model (Miller and Blair, 2009), which allows for the calculation of environmental impacts of a demand stimulus in an exporting region as:

$$\mathbf{C} = \mathbf{B} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \quad (1)$$

Let n_R be the number of regions, n_S be the number of industries and n_F be the number of fuel types. $\mathbf{y}$ is a column-vector of exports of length $n_R n_S$, with nonzero values in the entries of the exporting region and empty for the remaining values; $\mathbf{A}$ is a square technical coefficient matrix with side of length $n_R n_S$, expressing how many inputs from other sectors a given sector requires to generate a unit of output; $\mathbf{I}$ is an identity matrix; $\mathbf{B}$ is a

matrix of environmental interventions, with n_R rows and $n_R n_S$ columns, expressing carbon emissions in the electricity-generating region (in rows) per unit of economic output of the exporting region and sector (in columns); and **C** is a resulting column-vector of regional emissions of length n_R . This study specifies Eq. (1) directly in terms of a target exporting region to simplify the notation, the analysis can then be performed iteratively for all regions.

In order to study how a change in one region's electricity generation structure will impact the carbon intensity of an exporting industry of that region or a different region, the matrix of environmental interventions is decomposed as:

$$\mathbf{B} = \mathbf{F} \mathbf{S} \mathbf{T} \mathbf{E} \quad (2)$$

In the expression above, **E** is a matrix with n_R rows and $n_R n_S$ columns which shows how much electricity (in kWh) is consumed in each region to generate the total economic output of each industry (in yuan) in that same region; **T** is a matrix of inter-regional electricity transmission (Zhang et al., 2017), with $2n_R$ rows (to distinguish between production for domestic use and for inter-regional transmission) and n_R columns, which shows how much electricity is generated in a given region to satisfy consumption in another (and itself); **S** is an energy structure matrix, with $2n_R$ columns and $2n_R n_F$ rows, reflecting the use of different energy sources (coal, hydro, solar, etc) in the total electricity generation in each region (the factor of 2 in the number of rows and columns is required to distinguish between electricity production for intra-regional consumption and for inter-regional transmission); **F** is a carbon emission coefficient matrix with $2n_R$ rows and $2n_R n_F$ columns, which expresses the carbon emissions (MtCO₂) per electricity generated (kWh) of different energy sources (coal, hydro, solar, etc); finally, **B** in Eq.(1) is substituted by a matrix with $2n_R$ rows and $n_R n_S$ columns, which distinguishes between carbon emissions per unit of economic output for domestic use and for inter-regional transmission. Note that since the electricity sector is described separately from the rest of the economy, the rows and columns of matrix **A** corresponding to the electricity sector need to be set to zero to avoid double counting (Stromman et al, 2009).

The model described above is an energy-economic sequential hybrid model (Guevara and Rodrigues, 2016) based on the parallel models of Bullard and Herendeen (1975) or Joshi (1999), in which the energy use to generate electricity is described in physical units as separate matrices, and the rest of the economy is described in monetary units. The term hybrid denotes a combination of physical and monetary units. Hybrid analyses are useful, as the actual energy use data of the electricity sector can be inserted in the MRIO model in physical units, such that the MRIO model's reliability can be improved (Tian and Lin, 2017). Specifically, the main advantage of this formulation is that it becomes possible to use (non-monetary) energy data to describe electricity generation and inter-regional electricity transmission, which will become apparent when addressing the issue of data availability in the following section and scenario construction further below in this section. This provides more detailed information and is more rigorous than the alternative monetary data. A drawback of our approach is that life-cycle or upstream indirect impacts of electricity use (the emissions associated with the transport of energy or supporting services such as insurance) are not accounted for. However, closing this loop (making the system parallel) would require substantial effort in collecting data to disaggregate the use of non-energy inputs of the electricity sector (a single-sector in the economic matrix) into

several electricity generation technologies. Note also that the goal of the present study is not to study impacts of electricity generation but impacts of changes in energy structure on all emissions resulting from electricity generated along the supply chain of those exports.

This study is not only interested in calculating the impact of an isolated demand stimulus but, following the approach of Behrens et al. (2016), this study compares the impact of NE expansion between a reference year and a target year against a counterfactual scenario in which NE generation did not take place and is the same as in a reference year. In the counterfactual, the difference in electricity generation is provided by the most likely fossil fuel source, which in the case of China is coal. There are two separate aspects to consider. The first is to quantify the impact from the additional generation capacity beyond the one available in the reference year, as non-fossil fuel capacity that already existed would not have been removed. The second is the comparison of the two scenarios. It is convenient to define the column-vector of electricity demand, $\mathbf{u}$, of length $2n_R$ as:

$$\mathbf{u} = \mathbf{T} \mathbf{E} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} \quad (3)$$

such that the carbon emissions from a demand stimulus simplify to $\mathbf{F} \mathbf{S} \mathbf{u}$. The aim of simplification is to isolate the terms that will vary in the construction of scenarios. All terms in the right-hand side of Eq. (3) will change together, and can be compressed to a single variable.

This study focuses on the CO_2 impact of NE expansion and therefore restricts attention to the impact on CO_2 emissions of increased electricity output beyond that of the reference year. This is based on the assumption that no installation is expected to be decommissioned and the electricity generation that is present in the reference year will continue to generate over the time-span considered. This implies that the carbon emissions in the target year are split between embodied emissions from electricity generation by technologies already installed in the reference year, and embodied emissions from the increased capacity installed between the reference and target years:

$$\mathbf{C}_{\text{tar}} = \mathbf{F} \mathbf{S}_{\text{ref}} \mathbf{u}_{\text{ref}} + \mathbf{F} \mathbf{S}_{\text{tar}} (\mathbf{u}_{\text{tar}} - \mathbf{u}_{\text{ref}}) \quad (4)$$

In the expression above, subscript ‘tar’ describes what happens in the target year, and ‘ref’ describes what happens in the reference year. There are two terms on the right-hand side of Eq. (4): the first represents the emissions from the technology that remains from the reference year; the second represents the additional emissions from the technology installed between the reference and target years. Note that term $\mathbf{F}$ lacks a subscript since the emission coefficients per unit of electricity generated for each technology do not change over the time span of the study.

The impact of the counterfactual can use a similar expression as:

$$\mathbf{C}_{\text{alt}} = \mathbf{F} \mathbf{S}_{\text{ref}} \mathbf{u}_{\text{ref}} + \mathbf{F} \mathbf{S}_{\text{alt}} (\mathbf{u}_{\text{tar}} - \mathbf{u}_{\text{ref}}) \quad (5)$$

The subscript ‘alt’ describes the counterfactual scenario in which the observed NE expansion is replaced by coal. Note that the only change between Eq. (4) and Eq. (5) is the energy structure. Both the technology-specific emission coefficients and the electricity

demand are identical in both scenarios. This study therefore assumes that additional fossil-fuel capacity installed in the counterfactual scenario takes place in the region in which the NE generation in the target scenario is being replaced. Eqs. (4) and (5) can now be combined to obtain the net impact of NE expansion, ‘tot’, as:

$$\Delta C_{\text{tot}} = C_{\text{tar}} - C_{\text{alt}} = F (S_{\text{tar}} - S_{\text{alt}})(u_{\text{tar}} - u_{\text{ref}}) \quad (6)$$

This study is also interested in decomposing ΔC_{tot} into three components: intra-regional effect (the expansion of NE in the exporting region, ΔC_{self}), inter-regional electricity transmission effect (ΔC_{trans}), and supply-chain effect (ΔC_{supp}). The total effect is therefore obtained by partitioning as:

$$\Delta C_{\text{tot}} = \Delta C_{\text{self}} + \Delta C_{\text{trans}} + \Delta C_{\text{supp}} \quad 7(1)$$

$$\Delta C_{\text{self}} = C_{\text{tar}} - C_{\text{self}} = F (S_{\text{tar}} - S_{\text{self}})(u_{\text{tar}} - u_{\text{ref}}) \quad 7(2)$$

$$\Delta C_{\text{trans}} = C_{\text{self}} - C_{\text{trans}} = F (S_{\text{self}} - S_{\text{trans}})(u_{\text{tar}} - u_{\text{ref}}) \quad 7(3)$$

$$\Delta C_{\text{supp}} = C_{\text{trans}} - C_{\text{alt}} = F (S_{\text{trans}} - S_{\text{alt}})(u_{\text{tar}} - u_{\text{ref}}) \quad 7(4)$$

In the previous expressions S_{tar} and S_{alt} are, respectively, the energy structure in the target year in all regions, and the counterfactual energy structure in which all NE is replaced by coal. S_{self} and S_{trans} have some values that are identical to the energy structure in the target year and others that are identical to the counterfactual scenario, as explained below.

The first effect reflects the expansion of NE in the exporting region alone. Thus, S_{self} uses the counterfactual energy structure in the block for the domestic production of the exporting region and the historically observed energy structure in all other blocks. Therefore, in the counterfactual scenario, NE expansion for intra-region electricity generation did not occur in the exporting region, but did in all other regions, and even in the domestic production for intermediate inputs that export to other provinces. The two other effects are related to NE development occurring in other regions but propagating through different causal links: electricity transmission and supply-chain effects. To be able to split these two effects, this study uses the network approach of Rodrigues et al. (2016) to distinguish electricity generated for export to the exporting region, from the total electricity generation. Formally, this is achieved by explicitly considering two electricity sectors per region, both with the same emission coefficients, but one satisfying the demand of exporting region and the other satisfying the demand of all other regions. Then, regarding S_{trans} , the domestic electricity generation of exporting region uses the target energy structure and all other regions transmitting to the exporting region use the counterfactual energy structure.

This means that C_{trans} reflects the sum of intra-regional NE expansion and inter-regional electricity transmission effects, and C_{alt} reflects the sum of all effects. That is why each individual effect in Eqs. 7(2)-7(4) are expressed as the difference between sequential gross impacts, e.g., the impact of intra-regional NE expansion, ΔC_{self} , is the difference between C_{alt} and C_{trans} .

4. Data

Fossil fuel and electricity consumption data are obtained from the Comprehensive Energy Balance Table for each province in the *China Energy Statistical Yearbooks (CESY)* (NBS, 2003, 2008, 2010, 2015a). Data for generation in all 30 regions are derived from the *China Electric Power Yearbook (CEPY)* (CEPYEB, 2003, 2008, 2011, 2015). This dataset includes five electricity generation types (thermal power, nuclear, hydropower, wind, solar). Since sufficient data on the amount of thermal power generated from different fossil fuel types is lacking (e.g. thermal power generated from coal consumption), this study uses the net coal consumption rate for fossil-fired power plants (gce/kwh) in the *CESY* (NBS, 2003, 2008, 2010, 2015a) to convert physical coal to electricity generated. The main data source for fossil fuel consumption embodied in the transformation of thermal power are also from the *CESY* (NBS, 2003, 2008, 2010, 2015a). Electricity transmission data for provincial grids in 2007, 2010, and 2014 are from the *Annual Report of Power Market Transactions* (SGC, 2008, 2011, 2015). Electricity transmission data for provincial grids in 2002 are from the *CEPY* (CEPYEB, 2003). China's electricity transmission data are split between province-to-province transmission in six sub-national power grids and province-to-sub-national-grid transmission. This study uses Zhang et al., (2017)'s methods and assumptions to disaggregate province-to-sub-national grid transmission according to the spatial connection of transmission lines between the delivering side and receiving side. Data for transmission losses from the literature are used (CEPYEB, 2003, 2008, 2011, 2015; Kosuke K, 2003; Chen et al., 2014; Zhang et al., 2017).

This study utilizes MRIO tables of China's 30 provinces for 2002, 2007 and 2010 (Shi and Zhang, 2012; Liu et al., 2012; 2014). For lack of data, Tibet, Hong Kong, Macau and Taiwan have been excluded from China's MRIO tables. This study aggregates the 30 sectors in 2007 and 2010 tables to 21 sectors to match the 2002 table (see Table A.2 of Appendix). Large changes in NE were witnessed between 2010 and 2014 (as shown in Fig.1). Since official MRIO tables are available only to 2010, this study builds a projection for 2014. Ideally, this study would establish a new MRIO dataset for 2014 by implementing a survey on a large enough scale. But since establishing new MRIO datasets is time-consuming and costly, the RAS method (Lahr and de Mesnard, 2004) (a particular bi-proportional matrix balancing method (Rodrigues, 2014)) is utilized to update the MRIO table for 2014 in a similar way as performed by Lee et al., (2011), Cai et al., (2014), Chun et al., (2014) and Varela-Vázquez and Sánchez-Carreira (2015). This is described below.

First, this study computes the sum of rows and columns of the intermediate flow matrix for 2014 based on the 2014 data for output level, final demand, trade, and value added. This study then obtains the 2014 data for final demand and value added per region from NBS (2015b). Due to the lack of data for sectoral output in 30 provinces, this study considers economic growth rates of five major sectors (agriculture, industry, construction, transportation, and services) per province during the period 2010-2014, and uses a proportional adjustment approach to estimate sectoral outputs per province in 2014. Moreover, in order to quantify the changes in trade structure, this study uses the trade flows by sector in each region collected by Chinese Customs to build import and export vectors for 2014. Then, using the RAS method, the technical coefficient matrix (A) can be updated from a knowledge of the intermediate flow matrix in the base year (2010), and the row and column totals of the flow intermediate matrix for 2014. The updated technical

coefficient matrix reflects the changes in interdependencies between different sectors in China's economy during the period 2010-2014. Finally, the column-vector of export for 2014 is exogenously specified.

Since this study includes recorded data of economic output, final demand and international trade in 2014, and given the small timeframe considered, it expects that 2010 offers a good starting point for the application of the RAS method in projecting the economic structure of 2014. Note that by using a hybrid energy-economic model as described in Section 3, it is possible to use a physical description of inter-regional electricity transmission which is already available for the year 2014, so the RAS estimation is only performed for non-electricity sectors. Given the importance of electricity transmission to the subject of this study, potential uncertainties due to the introduction of the MRIO table for 2014 is greatly reduced. In order to apply the method described in Section 3, this study needs to specify a reference year. This study considers the reference year to be 2002, as it precedes the NE expansion as shown in Fig. 1.

5. Results

First, this study describes the impact of NE development on emissions embodied in exports over time, and reports the differences observed at the regional level. Then, this study presents the contribution of electricity transmission to emissions embodied in exports. Finally, this study evaluates the impact of NE on inter-regional CO₂ transfers.

5.1. CO₂ emissions embodied in provincial exports

Table 1 shows the CO₂ emissions embodied in provincial exports. China's CO₂ emissions embodied in exports were 583 Mt in 2002, 1801 Mt in 2007, 1632 Mt in 2010, and 1331 Mt in 2014, respectively. The national results are similar to previous work (Guo et al., 2012 with 688.15 Mt in 2002; Weitzela and Ma, 2014 with 1730 Mt in 2007; Zhang et al., 2015 with 2108 Mt in 2007, and 1616 Mt in 2010), which indicates that the proposed CO₂ emission accounting framework is reliable, and can be used for investigating the impact of NE development on embodied CO₂ emissions. Between 2002 and 2007, CO₂ emissions embodied in exports doubled. During the period 2007-2014, export-embodied carbon emissions decreased at an average annual rate of 3.7%. The distribution of emissions embodied in exports followed the distribution of China's exports at the provincial level. Between 2002 and 2010, export-embodied emissions were the highest in the eastern region with Guangdong as the largest, accounting for 22.8% of the total in 2002, increasing to 29.7% in 2014. The next most important provinces were Jiangsu, Zhejiang, and Shandong, with shares above 10%.

Table 1. Provincial carbon emissions embodied in exports (MtCO₂).

Province	Emissions embodied in exports (MtCO ₂)				Shares of provincial export- embodied emissions (%)			
	2002	2007	2010	2014	2002	2007	2010	2014
Beijing	13.65	19.64	21.27	8.87	2.34	1.09	1.30	0.67
Tianjin	17.63	31.92	17.21	11.47	3.02	1.77	1.05	0.86
Hebei	17.66	54.04	58.38	58.05	3.03	3.00	3.58	4.36
Shanxi	8.41	24.30	18.63	10.62	1.44	1.35	1.14	0.80
Inner Mongolia	4.40	11.97	16.16	8.00	0.75	0.66	0.99	0.60
Liaoning	59.47	86.96	53.95	23.68	10.19	4.83	3.31	1.78
Jilin	3.74	5.25	15.75	5.35	0.64	0.29	0.97	0.40

Heilongjiang	5.56	8.95	10.05	3.82	0.95	0.50	0.62	0.29
Shanghai	47.56	101.44	67.94	61.44	8.15	5.63	4.16	4.62
Jiangsu	83.24	346.76	338.56	255.33	14.27	19.26	20.75	19.19
Zhejiang	73.88	263.48	203.65	144.51	12.66	14.63	12.48	10.86
Anhui	5.22	10.20	15.11	23.99	0.90	0.57	0.93	1.80
Fujian	9.29	36.65	29.56	33.07	1.59	2.04	1.81	2.49
Jiangxi	1.10	3.00	4.28	5.59	0.19	0.17	0.26	0.42
Shandong	71.81	284.55	207.04	144.79	12.31	15.80	12.69	10.88
Henan	7.70	20.06	28.13	51.90	1.32	1.11	1.72	3.90
Hubei	1.90	7.23	10.23	9.00	0.33	0.40	0.63	0.68
Hunan	1.97	5.49	7.84	6.46	0.34	0.30	0.48	0.49
Guangdong	132.71	434.47	453.89	394.45	22.75	24.13	27.82	29.65
Guangxi	1.26	4.11	5.50	6.17	0.22	0.23	0.34	0.46
Hainan	0.27	0.49	0.61	3.15	0.05	0.03	0.04	0.24
Chongqing	1.10	3.00	3.60	18.66	0.19	0.17	0.22	1.40
Sichuan	3.64	7.19	8.10	11.18	0.62	0.40	0.50	0.84
Guizhou	1.30	4.11	3.36	2.76	0.22	0.23	0.21	0.21
Yunnan	1.24	4.60	6.02	3.92	0.21	0.26	0.37	0.29
Shaanxi	2.76	5.66	11.03	14.12	0.47	0.31	0.68	1.06
Gansu	1.23	4.79	2.97	1.76	0.21	0.27	0.18	0.13
Qinghai	0.09	0.49	0.76	0.83	0.01	0.03	0.05	0.06
Ningxia	0.82	2.15	4.63	2.68	0.14	0.12	0.28	0.20
Xinjiang	2.77	7.69	7.27	4.88	0.47	0.43	0.45	0.37
Total	583	1801	1631	1331	100	100	100	100

5.2. Total impact of non-fossil electricity development

Fig.3 presents the total impact of NE expansion on export-embodied carbon emissions over the period through the three propagation effects (intra-regional, electricity transmission, and supply-chain). NE generation resulted in a mitigation of 203 Mt, 244 Mt, and 259 Mt in 2007, 2010, and 2014 respectively. As a percentage of the total emissions embodied in exports, NE development resulted in a CO₂ reduction of 11.3% in 2007, 14.9 % in 2010 and 19.5% in 2014, respectively. There was a significant impact during 2010-2014 due to the large growth of NE from 2010 onwards. The intra-regional effect comprised about 60% of the total NE impact during the whole period. Electricity transmission had a major role in CO₂ savings, resulting in a reduction of 50 Mt, 53 Mt, and 62 Mt in 2007, 2010 and 2014 respectively. Emission reductions as a percentage of the total export-embodied carbon emissions were 2.8% in 2007, 3.2% in 2010, and 4.6% in 2014. Additionally, with the expansion of grid interconnections across China in the future (Li et al., 2016), this phenomenon is likely to intensify, suggesting that the interests of China and high-income nations in climate negotiations will be further aligned. The supply-chain effect was also significant, resulting in a reduction of 41 Mt in 2010, dropping to a net saving of 39 Mt in 2014. These results indicate that the ongoing transition of China toward NE has contributed substantially to reducing carbon leakage in international trade.

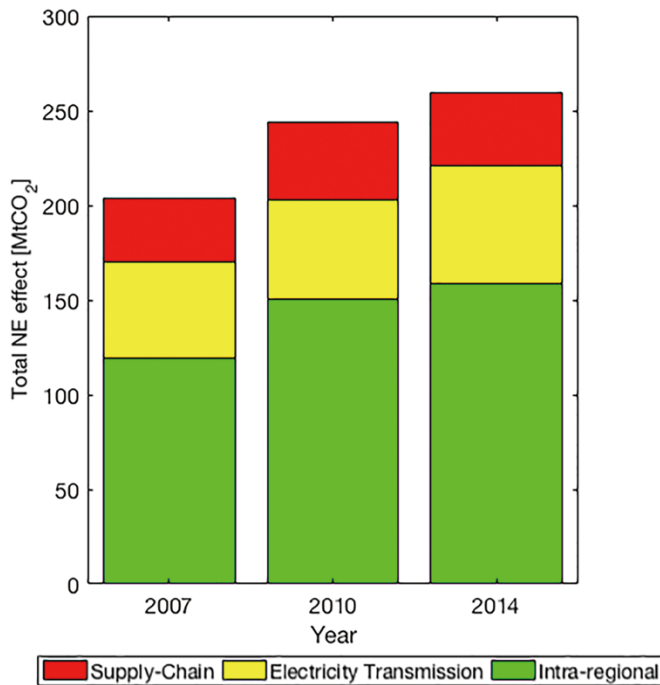


Fig.3. Total impact of NE on CO₂ emissions embodied in exports by three propagation effects (2007-2014).

5.3. Spatial distribution of the impact of non-fossil electricity

Given the substantial differences in NE development among provinces, it is important to investigate the spatial distribution of NE impacts through the three propagation effects across provinces and over the years. Fig.4 shows the largest impact in 12 provinces over the period 2007-2014. The impact of NE development generally followed the provincial distribution of export-embodied emissions. As the most important trade provinces in China, Jiangsu, Zhejiang, and Guangdong had the largest carbon emission reductions. The intra-regional effect had a major role in CO₂ savings in these provinces, contributing to more than 50% of the total NE impact. Most provinces were influenced heavily by the intra-regional effect. Hebei and Shandong had a relatively smaller impact of NE than Sichuan and Hubei, even though their export-embodied emissions were larger. The provinces with abundant NE resources saw the largest intra-regional effect, such as Hubei, Sichuan, Yunnan, and Guangxi.

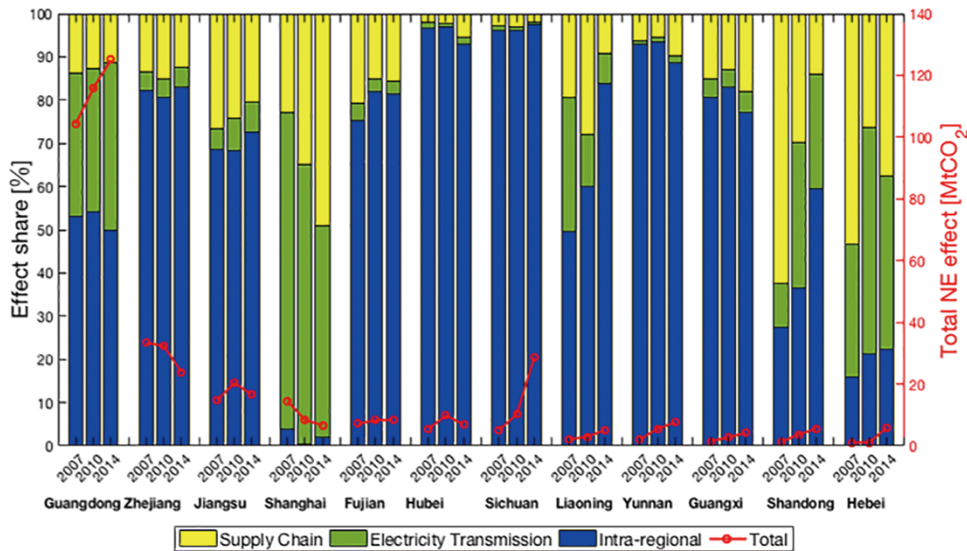


Fig.4. Largest impacts of NE on CO₂ emissions embodied in exports in 12 provinces (2007-2014).

In some provinces, the effect of electricity transmission was responsible for very large emission savings. This implies that the impact of NE might be underestimated if only the generation side is considered. For example, Shanghai showed a mitigation of more than 5 Mt reduction from 2007 to 2014, with electricity transmission playing an important role due to the import of hydropower from the western region to the eastern region. From 2007 to 2014, mitigated emissions due to electricity transmission comprised over 48% of the total NE impact in Shanghai. Also, electricity transmission was an important driver for the reduction of CO₂ emissions in Hebei. Earlier, in 2007, electricity transmission yielded relatively small reductions in CO₂ emissions in Hebei due to cheap, coal-fired electricity imported from adjacent provinces. While Hebei's neighboring provinces (e.g. Inner Mongolia and Shanxi) did expand NE generation over the period, the effect of electricity transmission comprised 40.1% of the total impact, resulting in a reduction of 2.39 Mt in 2014. Clearly, whether electricity transmission impacts emission mitigation depends on the level of NE development in neighboring provinces. This is because NE expansion in neighboring provinces will reduce the imports of coal-fired electricity.

Another factor influencing the impact of NE expansion in Shanghai and Hebei was from supply chains. In 2014, Shanghai's supply-chain effect resulted in a reduction of 3.26 Mt, comprising 49% of the total impact. Shanghai is the economic center of the eastern region but has very limited energy resources, thus, its demand for exports stimulates the production of upstream industries (e.g. electricity sector) in the central and western regions (Zhong et al., 2017). Since the central and western regions provide a large quantity of intermediate products to Shanghai, NE development in these regions reduce Shanghai's export-embodied emissions. In 2007, the supply-chain effect was the most important factor underling Hebei's large NE impact, accounting for 53% of the total NE impact. Although the share of supply-chain effect in Hebei reduced to 38% in 2014, it made up a much larger share of its total emission savings than its intra-regional effect.

Since Hebei has become China's workshop and a major manufacturing base, neighboring provinces (e.g. Shanxi and Inner Mongolia) have been the primary providers of intermediate products for Hebei's exports (Wang et al., 2017). Overall, the expansion of wind power in the northern provinces after 2007 helps Hebei to reduce export-embodied emissions.

5.4. Intra-regional effect of non-fossil energy development

Since the intra-regional effect reflects the influence of NE development in the exporting region itself, and its spatial distribution is consistent with the distribution of China's NE resources at the provincial level, this study further splits the intra-regional effect by NE types. Fig.5 reports the intra-regional effect in twelve important trade provinces by NE type over the study period. The most important trade provinces, Guangdong, Zhejiang and Jiangsu, tend to be influenced by the development of nuclear power, as nuclear power is mostly located on or near the eastern coastline. From 2007 to 2014, the intra-regional effect in Liaoning and Fujian increased rapidly by 109% and 28% respectively, with the construction of nuclear power stations in both provinces. The development of nuclear power was responsible for 45% and 24% of their total intra-regional effects respectively in 2014. Hydropower had the largest impact in lowering emissions in the southwestern provinces. The impact of hydropower accounted for about 99% of the intra-regional effects of Hubei, Sichuan, Yunnan, and Guangxi during the period 2007-2014. Wind power development drove significant reductions in embodied emissions of Shanghai, Shandong, and Hebei. The effect of wind power accounted for more than 90% of Shanghai's total intra-regional effect between 2007 and 2014. The share of emission reductions from wind power in Shandong increased from 54% in 2007 to 96% in 2010, and then decreased to 93% in 2014. In 2014, the share of the wind power impact in Hebei's total intra-regional effect increased from 54% in 2007 to 90%. The impact of solar power in Shanghai by 2014 remained small but accounted for 10% of the total intra-regional effect by 2014.

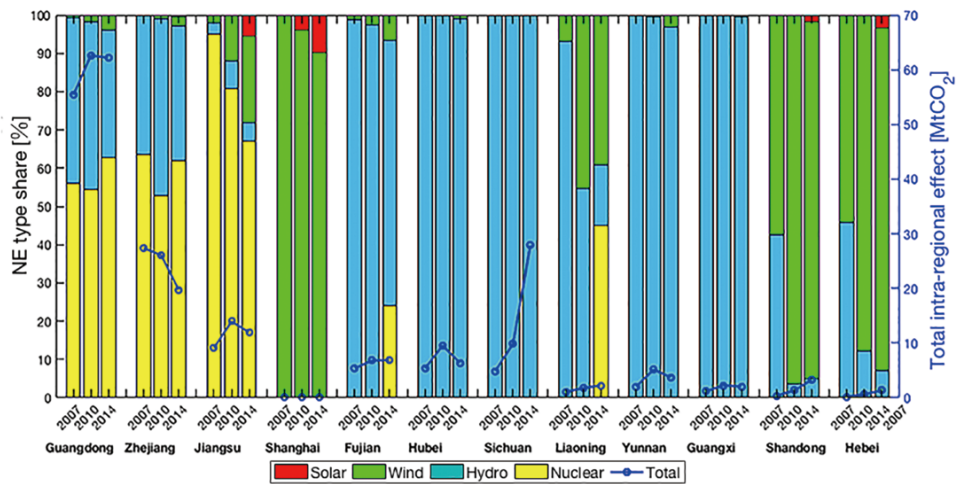


Fig.5. Intra-regional effects in 12 important provinces by NE type (2007-2014).

5.5. Electricity transmission and impact of non-fossil electricity

Given the observed, substantial provincial differences in NE development, it is interesting to further investigate how electricity transmission brought about these emission reductions. Fig.6 presents the CO₂ impact of electricity transmission among eight, aggregated regions (listed in Table A.3 of Appendix A). In general, electricity transmission resulted in a relatively small reduction of emissions in the Southwest and Central regions, while increased electricity imports resulted in a large reduction of CO₂ emissions in the South Coast and East Coast regions.

Mitigated emissions were seen largely in the South Coast and East Coast regions as electricity transmission infrastructure focused on bringing in hydropower from the Southwest and Central regions to the South Coast and East Coast regions. Regardless of the electricity transmission from the Southwest region to the South Coast region, overall CO₂ emissions in the South region increased by 22.51 Mt in 2007, 30.16 Mt in 2010, and 41.08 Mt in 2014. Due to the electricity transmission from the Central region to the East Coast region, CO₂ emissions in the East Coast region could be reduced by 10.10 Mt in 2007, 5.17 Mt in 2010, and 3.26 Mt in 2014. The utilization of transmission lines from the North region to the East Coast region facilitated the expansion of wind power in the North region, resulting in a reduction of 0.69 Mt in 2010 and 0.72 Mt in 2014. Also, after 2010, the reduction of CO₂ emissions in the North region due to the electricity transmission effect was mostly related to the electricity transmission from the Northwest region, with mitigations of 0.95 Mt in 2010 and 0.98 Mt in 2014. However, the exported electricity in the Northwest region had limited effect on the export-embodied emissions in the East Coast and South Coast regions. Therefore, the government may need to enlarge the outward transmission capacity from the Northwest region and concentrate the connections to the East Coast and South Coast regions.

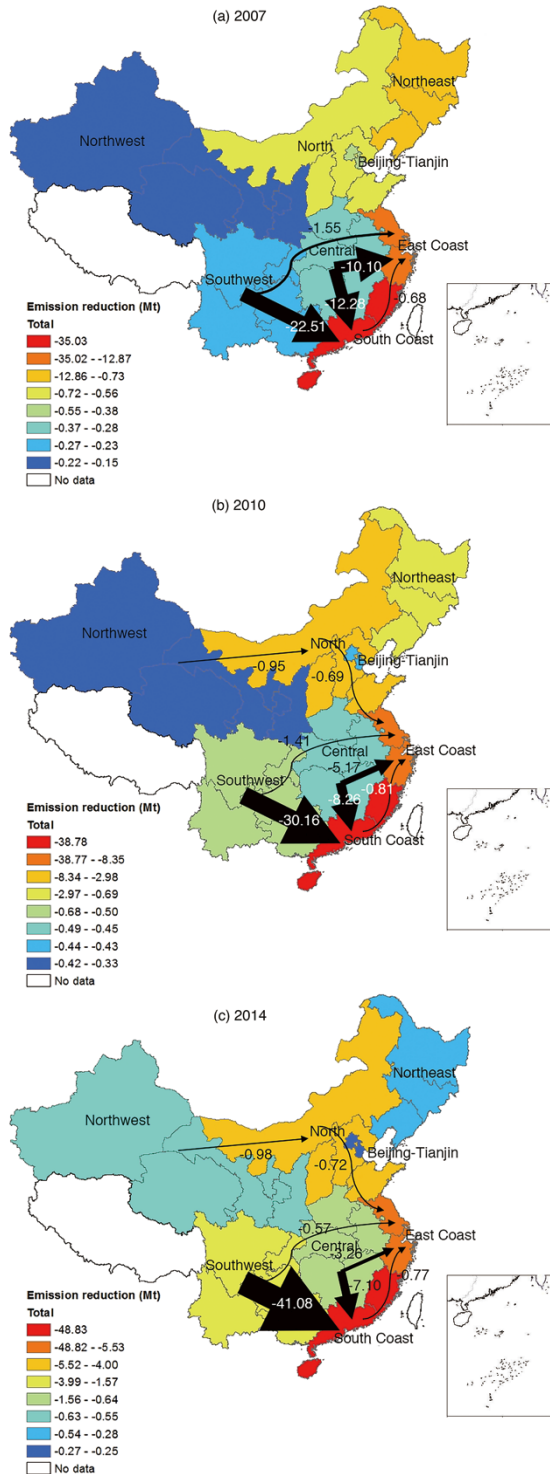


Fig.6. Largest impacts of inter-regional electricity transmission among eight, aggregated regions (2007-2014). Note: The shading in each region indicates the total impact induced by electricity transmission.

5.6. Supply chain and impact of non-fossil electricity development

Given the close linkage between production in the coastal eastern region and inputs from the central and western regions (Zhao et al, 2015), and the fact that NE is predominantly located in the western and central regions (as shown in Fig.2), investigating the impact of NE development on inter-regional CO₂ emission transfers gives further insight. Fig.7 presents the impact of NE development on inter-regional CO₂ flows induced by exports among eight regions.

In 2007, NE development in the Southwest region resulted in a significant reduction of CO₂ embodied in the intermediate inputs to support the exports of the South Coast (7.51 Mt) and East Coast (2.81 Mt) regions. CO₂ emissions in the South Coast region induced by the exports of the East Coast region showed reductions of 3.07 Mt. The inter-regional CO₂ flow from the Central region to the South Coast region showed reductions of 2.89 Mt. In 2010, CO₂ emissions in the Southwest region induced by the exports of the South Coast region saw the largest impacts (7.22 Mt), with the inter-regional CO₂ flow from the Southwest region to the East Coast region the second largest (2.98 Mt). The reason is that the East Coast and South Coast regions are generally located downstream in the supply chain, and need large resources from other regions. The remarkable reduction in the inter-regional CO₂ flow from the North region to the East Coast region (1.34 Mt) were primarily due to wind power development, evidenced by the large increases of wind power generation in Hebei and Shandong. In addition, with wind power development in the Northwest region, the indirect impacts of NE development in the Northwest region on the export-embodied emissions in the East Coast region expanded to 1.74 Mt. In 2014, the impact of NE development on CO₂ flows from the Central region to the East Coast and South Coast regions declined slightly. This is consistent with previous findings that the emissions embodied in the net trade from the Central region to the East Coast region has declined after 2010 due to the changes in regional production and consumption structure (Mi et al., 2017). However, the impact of NE on the CO₂ flow from the Southwest region to the South Coast region was still the largest (6.48 Mt). Moreover, the majority of NE impacts were seen within the CO₂ flow from the Southwest region to the East Coast region, reaching a maximum reduction of 4.71 Mt CO₂. These show that the NE development in other regions is still significant for reducing embodied emissions in the East Coast region.

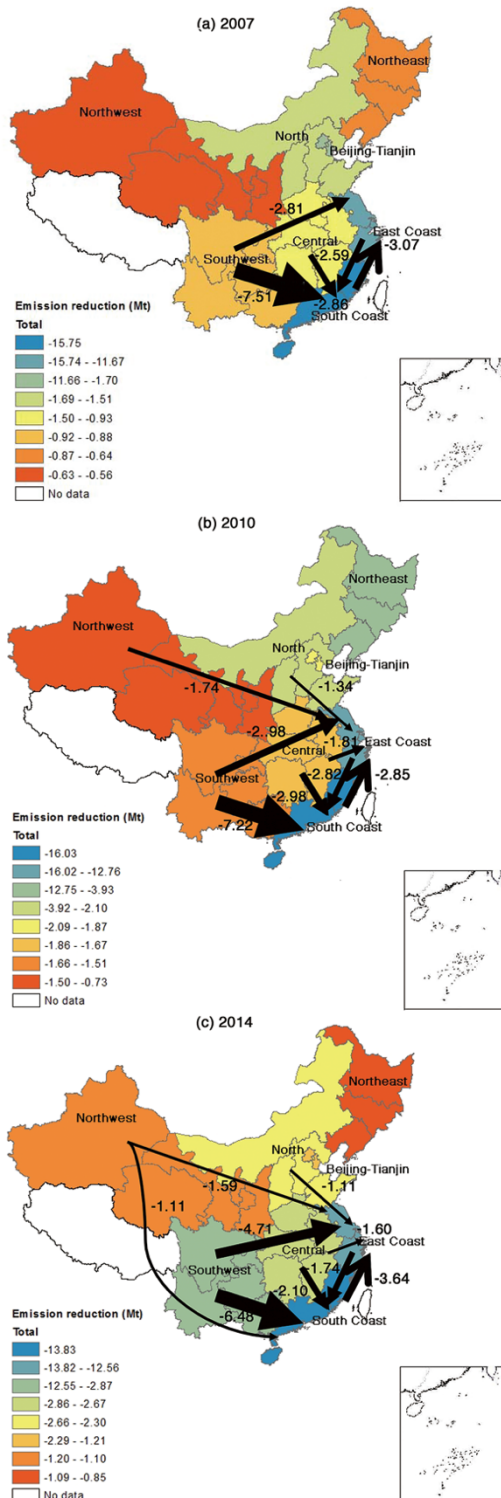


Fig.7. Largest supply-chain effects among eight, aggregated regions (2007-2014). The shading in each region indicates the nonlocal impact induced by NE development in other regions.

Based on the results in Section 5.3, due to the distribution of NE resources, the supply-chain effects in Shanghai and Hebei were much larger than their intra-regional effects. In order to analyze the most noteworthy inter-regional CO₂ flows through which nonlocal NE development exerted significant impacts on the embodied emissions in Hebei and Shanghai, the key inter-regional CO₂ flows (as shown in Table 2) are picked up. Hebei saw the largest emission reductions due to Guangdong's NE development in 2007 (0.07 Mt), increasing to 0.10 Mt in 2010. Since the intermediate input of Hebei was mainly supplied by neighboring provinces, wind power development in Inner Mongolia started to have a major role in Hebei's CO₂ savings after 2010, driving a reduction of 0.10 Mt in 2010, and 0.32 Mt in 2014. In 2007, the nonlocal impact of Shanghai generally came from neighboring provinces (Zhejiang and Jiangsu). In 2007, NE development in Zhejiang resulted in a reduction of 0.70 Mt CO₂ embodied in Shanghai's exports via inter-regional economic linkages, expanding to 1.21 Mt in 2014.

Table 2. Largest supply-chain effects for Hebei and Shanghai (MtCO₂).

Year	Province r	Province s	effect induced by province r	Total effect
2007	Guangdong	Hebei	-0.07	-0.58
	Sichuan		-0.06	
	Zhejiang		-0.06	
	Zhejiang	Shanghai	-0.78	-3.32
	Guangdong		-0.64	
	Sichuan		-0.28	
2010	Inner Mongolia	Hebei	-0.10	-0.80
	Guangdong		-0.10	
	Sichuan		-0.07	
	Guangdong	Shanghai	-0.56	-2.92
	Zhejiang		-0.47	
	Sichuan		-0.24	
2014	Inner Mongolia	Hebei	-0.32	-2.24
	Sichuan		-0.30	
	Hubei		-0.28	
	Zhejiang	Shanghai	-1.21	-3.27
	Jiangsu		-0.77	
	Hubei		-0.16	

Note: Column 4 indicates that the impact of NE development in province r on export-embodied emissions of province s. Column 5 indicates that the total impact of NE development in other provinces on export-embodied emissions of provinces.

5.7. Summary and discussion

This study applies a hybrid MRIO model with inter-provincial electricity transmission to assess the impact of NE development on the carbon emissions embodied in the exports of China's 30 provinces. The changes in carbon emissions are estimated by comparing historical data with a counterfactual without NE development. Such an investigation presents a comprehensive picture of NE impacts, including historical evolution, spatial distribution, mode of propagation and energy types, which can be used to test the applicability of national NE policies implementation.

Large-scale NE development reduced export-embodied CO₂ emissions by 203Mt, 244Mt, and 259 Mt export-embodied CO₂ in 2007, 2010, and 2014 respectively, which was

equivalent to 11.3% in 2007, 14.9 % in 2010 and 19.5% in 2014 of the total carbon emissions embodied in exports, respectively. Provinces with a large amount of export-embodied emissions, such as Guangdong, Jiangsu, and Zhejiang, have seen a relatively high carbon impact of NE as nuclear power and hydropower have been expanded. This shows that the expansion of NE in China has significantly reduced the potential carbon leakage in international trade. However, the provincial carbon impact of NE did not correlate directly with the distribution of export-embodied emissions. Several major trade provinces, such as Shandong and Hebei, had a relatively low carbon impact of NE. In contrast, provinces such as Hubei, Sichuan, and Yunnan, which had small amounts of export-embodied emissions, have driven large decreases in CO₂ emissions as hydropower has expanded over a long period.

Furthermore, NE impacts are divided into three modes: intra-regional, electricity transmission, and supply-chain. Since the intra-regional effect matches up well with NE resource across regions in China, most provinces with large NE impacts were mainly affected by intra-regional NE expansion. This study highlights the relationship between electricity transmission and the carbon impacts of NE. Electricity transmission led to CO₂ emission reductions of 50 Mt in 2007, increasing to 62 Mt in 2014. Overall, the exported electricity of the Central and Southwest regions made a large contribution to reducing the emission tensions in the East Coast and South Coast regions. The exported electricity of the Northwest region could also effectively reduce the CO₂ emissions in the North region. Moreover, the facilitation of mitigation due to electricity transmission depends on the level of NE development in neighboring regions. Initially, electricity transmission might lead to small emission reductions due to increasing imports of low-cost coal-fired electricity. As the amount of NE increases, CO₂ emissions will start to reduce. This study gives further resolution of the impact of NE development on inter-regional CO₂ flows, and traces indirect impacts induced by other regions' NE development. NE development in the Central and Southwest regions brought about a significant reduction of export-embodied CO₂ emissions in the South Coast and East Coast regions, as close economic linkages existed between them. NE development in neighboring provinces resulted in a mitigation of export-embodied CO₂ emissions in Hebei and Shanghai via inter-regional economic connections.

Fruitful directions for further research could focus on the carbon impact of expansion of NE infrastructure, as this work only explores the operational, 'in-use' effect of NE. Second, the impact of NE development on the carbon emissions embodied in China's exports to particular importing countries (i.e. the United States) would be a valuable further effort. Finally, this study provides a quantitative framework that can be applied to other countries. Further studies could also be expanded by performing a spatially-explicitly, time-series analysis over a longer period.

6. Conclusions and policy implications

This study explores the regional patterns of the impact of NE expansion on China's export-embodied carbon emissions. The contribution of electricity transmission and supply-chain effects to overall CO₂ savings is analyzed. The findings highlight the impact of NE development on inter-regional CO₂ flows, and the importance of electricity transmission, which helps clarify how the impact of NE development is generated and transmitted. Considering the rapid expansion of NE in China, a historical investigation of the evolution of NE effects at the provincial level informs energy planning and

management. This knowledge can be used to make further scenarios for the future, and serves as a basis for the evaluation of NE regulations. Based on the results above, several policy implications can be given.

First, NE policies need to take spatial features into consideration given China's regional heterogeneity. Since more than half of China's export-embodied emissions were driven by top trade provinces, a better understanding of the obvious regional differences in export-embodied emissions will support a wider range of NE development options, and is beneficial to national and global climate policy. Specifically, if these top trade provinces have reduced export-embodied emissions due to NE development, that also triggers to a change in the total national export-embodied emissions, which then has flow-on impacts on global carbon emissions. Thus, when formulating NE development plans, paying more attention to provinces with a low-level of NE development and fast-growing outsourcing emissions would contribute to developing reasonable NE targets among provinces. For example, since NE has not been fully exploited in Hebei and Shandong, a reasonable regional NE development plan could be formulated for Hebei and Shandong to reduce the carbon leakage in international trade in the long term.

Second, the improvement of electricity transmission is an optimal way to increase carbon savings brought by NE development. The basic spatial structure of electricity transmission, in which the coastal regions imported NE from the inland regions, has been established in China. However, the current electricity transmission grid for wind and solar power is limited. NE delivery across regions still relies on hydropower. Though there are good wind and solar resources in the Northwest region, they are not yet transmitted to the East Coast region. Moreover, the expansion of wind power in the Northeast region does not obviously impact the carbon emissions in the North region. These results are important for electricity transmission system designers. If the expansion of wind and solar power continues, two inter-regional electricity transmission lines in different directions would need to be considered.

Third, significant export-embodied emission reductions in the coastal regions can be obtained from the NE development in the inland regions via inter-regional economic linkages. This provides useful insights regarding to the role of NE development in decarbonizing global supply chains. Supply-chain and electricity transamination effects are heavily intertwined, as they both strengthen the transfer of carbon impacts due to NE development from one region to another. However, these two different effects, inter-regional economic relations and electricity transmission, are generally addressed by different policy tools. This means that when planning NE expansion, both effects should be considered and proposed policies should be synergistic. Since the inland regions generally have low mitigation costs due to abundant resources, diffusion of NE technologies there may reduce the nationwide mitigation costs. The supply-chain effect of NE development is more significant for neighboring regions. This suggests that policies promoting the joint control of export-embodied emissions in surrounding regions can complement existing approaches to intensify the impact of NE development on reducing export-embodied emissions.

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Appendix

Table A1. Comparison between the different studies of China's export-embodied carbon emissions based on MRIO model.

Author /s	Data Year	Methods	Research Topic	Main Results
Qi et al., 2014	2007	MRIO and CGE	The impact of economic restructuring on export-embodied emissions	Increasing export taxes could decrease 44 MtCO ₂ embodied emissions, equivalent to a 3.7% decrease.
Liu et al., 2016a	2007	IO	The assessment of export embodied emissions using firm heterogeneity information	Ignoring firm heterogeneity caused China's export-embodied CO ₂ emissions in 2007 to be overestimated by 20% .
Tang et al., 2017	2012	IO and multi-objective programming	The impact of trade restructuring on export-embodied emissions	Trade restructuring could reduce China's net export-embodied emissions by 3.26%, 9.33% and 14.58% under low, moderate and high scenarios, respectively.
Zhao et al., 2017b	2000 - 2014	MRIO	The carbon impact of trade between China and major trading partners in the Asia-Pacific	During 2000-2006, the expansion of China's intermediate exports with major trade partners in the Asia-Pacific increased China's carbon emissions, with annual growth rates of 20%. After 2006, the impacted carbon emissions fluctuated around 400 MtCO ₂ .
Weber et al., 2008	1987 - 2005	IO	The trend of export-embodied emissions	In 2005, almost one-third of China's emissions (1700 Mt CO ₂) were due to the production of exports.
Xu et al., 2011	2002 - 2008	IO and SDA	Driving factors of export-embodied emissions (emission intensity, economic structure, export composition and export volume)	During 2002-2008, the increase of export-embodied emissions was attributable to the change of export composition. The decline in emission intensity counterweighed the growth of embodied emissions.
Liu et al., 2017	2007	IO	Estimation of export-embodied emissions using a non-competitive import IO approach	Using a non-competitive import IO approach, the net CO ₂ emissions embodied in China's trade in 2007 (400 Mt) were much lower than previous estimations.
Tian and Lin, 2017	2002 - 2012	Hybrid IO	The impact of green productivity growth on emissions embodied in China's industrial exports	The total emissions embodied in China's industrial exports increased more than 100% during 2002-2007, with small variation during 2007-2012. Technological improvement could reduce embodied emissions.
Xu et al.,	2011	MRIO	The estimation of export-embodied	The result based on traditional methods caused a substantial

2017			emissions	overestimation, equaling to almost one-third of the total export-embodied emissions.
Peters et al., 2011	1990 - 2008	MRIO	The emission transfers via international trade	The emissions induced by the production of exports in China accounted for 18% of the growth in the global CO ₂ emissions.
Deng et al., 2016	1995 - 2009	MRIO and SDA	Driving factors analysis (emission coefficient, Leontief inverse matrix and export scale)	The changes of direct emission coefficients led to the decrease in embodied emissions, while the variations of Leontief inverse matrix led to the increase in embodied emissions
Andersson, 2018	1995 - 2008	MRIO, Statistical test	The impact of China policy reforms on export-embodied emissions	Trade liberalization, environmental institutions and exchange rate policies were important institutional factors illustrating the growth of embodied emissions.
Zhao et al., 2016	1995 - 2009	MRIO, HEM, and SDA	Driving factors of carbon emissions embodied in China-US trade (emission intensity, energy use structure, energy intensity, trade structure, technology level, export market shares of final products, total demand)	“Trade structure of intermediate products at home” and “export market shares of final products at home” factors showed the largest positive effects on embodied emissions.
Zhao et al., 2017a	1995 - 2009	MRIO and GLMDI	Driving factors of CO ₂ emissions per value added (EpV) in the trade of China and USA (emission coefficient, IO structure and value added coefficient)	The EpV of China’s exports was 6.35 times that of USA in 1995, and this ratio reached 7.43 in 2009. IO structure had the largest effect on the expansion of EpV gaps between China and USA.
Wu et al., 2016b	2000 - 2009	Two region MRIO and LMDI	Driving factors of changes of CO ₂ emissions embodied in China-Japan trade (export volume, export structure, emission intensity)	Export volume was the main driver for the increase of embodied emissions, while emission intensity reduction contributed to reducing embodied emissions.
Li and Hewitt, 2008	2004	IO	The impact of China-UK trade on global CO ₂ emissions	China-UK trade led to an additional 117 Mt of CO ₂ to the global CO ₂ emissions in 2004, accounting for 19% of the UK’s total emissions and 0.4% of the global emissions.
Su and Ang, 2010	1997	MRIO	The impact of spatial aggregation on export-embodied	The impact of spatial aggregation on the embodied emissions could be achieved through affecting the total

			emissions	emission intensities.
Feng, 2012	2007	MRIO and SDA	Driving factors of provincial CO ₂ emissions embodied in exports	Exports in the developed regions were supported by emissions occurring in the less developed regions of China.
Guo et al., 2012,	2002	MRIO	Characteristics of export-embodied CO ₂ emissions at the provincial level	The eastern region accounted for a large proportion in China's export-embodied CO ₂ emissions. The net transfer of embodied emissions was from the eastern region to the central region.
Meng et al., 2013	2002 and 2007	MRIO	CO ₂ emissions spillover effects caused by partner region's exports	The exports of the South Coast and East Coast regions had the largest spillover effect on CO ₂ emissions in the other regions.
Weitzel and Ma, 2014	2007	MRIO	The effect of export processing and inter-regional trade on export-embodied emissions	The estimated embodied emissions using the MRIO model (1730 Mt CO ₂) and the model considering export processing (1630 Mt CO ₂) were both lower than estimations of the standard IO model (1782 Mt CO ₂) in 2007.
Liu et al., 2015a	1997 - 2007	MRIO	The estimation of carbon emissions embodied in the demand-supply chain for exports	The largest inter-regional net transfer of embodied in the demand-supply chain for export was from the less developed regions to the developed regions.
Tang et al., 2015	1997 - 2010	MRIO	The inter-regional spillover and feedback effects induced by exports	The strong spillover effects caused by exports showed in the coastal regions, while the strong feedback effects caused by exports showed in the inland regions.
Wang et al., 2015	2007	MRIO and Kaya decomposition analysis	The impact of carbon flows among regions on export-embodied emissions	Almost 40% of the emissions embodied in the coastal regions' exports occurred in the inland regions of China in 2007 via inter-regional economic linkages.
Zhang and Tang, 2015	2007 - 2010	MRIO and LMDI	Driving factors of carbon embodied in provincial exports (emission intensity, IO structure, export structure, regional distribution and export scale)	During 2007-2010, the decrease in the total export-embodied emissions of most provinces was caused by the change of IO structure. The decline of emission intensity also decreased the export-embodied emissions in most provinces, especially in the eastern provinces.
Liu et al., 2015b	2007	MRIO and IDA	Driving factors of provincial export-embodied emissions (trade volume, trade structure, emission intensity)	The net emissions embodied in China's exports were mainly due to the coal-dominated energy structure and the high energy intensity of some exporting provinces and sectors.
Mi et al.,	2007 -	MRIO and SDA	Driving factors of provincial export-	The export-embodied emissions declined during 2007-2012 due to the

2017	2012	embodied emissions (trade volume, trade structure, emission intensity)	changes of production structure and the improvement of production efficiency. The net emission flows from the western region to the eastern region declined due to the expansion of consumption scale and the adjustment of economic structure.
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Table A2. Sector classifications for the Chinese economy.

Code	Sector
AGR	Agriculture
MC	Mining
FD	Food
TEX	Textile
TF	Processing of Timber and Furniture
PP	Paper and Paper Products
PC	Petroleum Refining and Coking
CHE	Chemical
NMP	Non-metallic Mineral Products
SPM	Smelting and Pressing of Metals
MP	Metal Products
GE	General Equipment
TE	Transport Equipment
EME	Electric Machinery and Equipment
EE	Electronic Equipment
IM	Instruments and Machinery of Cultural Activity and Office Work
OM	Other Manufacturing
ELE	Electricity
CON	Construction
TRA	Transportation
SE	Services

Table A3. Region classifications.

Region	Province that included in each region
Beijing-Tianjin	Beijing and Tianjin
North	Hebei, Shanxi, Inner Mongolia and Shandong
Northeast	Liaoning, Jilin and Heilongjiang
East Coast	Jiangsu, Shanghai and Zhejiang
Central	Henan, Anhui, Hunan, Hubei and Jiangxi
South Coast	Fujian, Guangdong and Hainan
Southwest	Sichuan, Chongqing, Guizhou, Yunnan and Guangxi
Northwest	Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang

Chapter 4

Impact of the expansion in non-fossil electricity infrastructure on China's carbon emissions

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Submitted to Applied Energy on January 2018, under review

Abstract

In recent years, China has embarked upon an ambitious roll-out of non-fossil electricity (NE) investments. This has led to substantial reductions in carbon emissions, and is expected to continue doing so in the future. However, NE investments also have a significant carbon footprint, in the form of the construction, transportation and assembling of the NE infrastructure itself. This paper addresses two main questions: 1) How do NE investments impact CO₂ emissions in China? and 2) How are such impacts distributed within China? To answer these questions, we use a multi-region input-output (MRIO) model to assess the emission impacts of investments compared with operational impacts. As there was a large surge in the installed capacity during the analysis period (2002 to 2010) we considered a counterfactual scenario in which NE expansion did not occur and generation followed historical patterns (i.e. using fossil energy). Results indicate that NE investments resulted in a net emission increase of 16.21 Mt, 28.71 Mt and 47.29 Mt in 2002, 2007 and 2010 respectively, while the net emission reduction during the operational phase of electricity generation was, respectively, 48.84 Mt, 81.83 Mt and 129.48 Mt per year. NE investments led to a significant increase of emissions in the northern, northeastern and northwestern provinces with rapid development of wind power. Moreover, through supply chains, a spatial pattern in which developed regions (e.g. east) outsource carbon impact of NE investments to developing regions (central, north), has formed in China. The carbon impacts of NE investments are often transferred to adjacent regions.

Keywords: CO₂ emissions; non-fossil electricity; investment; multi-regional input-output model

1. Introduction

The surface temperature of the earth has risen by nearly a degree in the past century (IPCC, 2001). In view of the current environment concerns, the international community has reached the world's most important agreement to address climate change (Paris Agreement) in December 2015 (UNFCCC, 2015, Tambo et al., 2016). China has also initiated a series of measures to lead the fight against climate change (Chen and Groenewold, 2015). Among these, the 13th Five Year Plan (2016-2020) set a target to reduce carbon intensity by 18 percent by 2020 compared to the 2015 level (Hu et al., 2016, Wu et al., 2017). Since the substitution of fossil fuels by non-fossil electricity (NE) can reduce emissions, in the Intended Nationally Determined Contribution (INDC) released on June 30, 2015, the Chinese government proposed a target of raising the share of non-fossil fuels in primary energy consumption to 20% by 2030 (Yang et al., 2016).

Furthermore, China's 13th Five-Year Development Plan (2016-2020) provides for an investment of 2,500 billion yuan in NE by 2020 (NDRC, 2016).

Against this background, the environmental impact of NE development in China has attracted significant attention (Qi et al., 2014, Long et al., 2015, Mitta et al., 2016, Wu et al., 2016, Chen and Geng, 2017, Ito, 2017, Zhao et al., 2017). However, most of studies investigated the effect of NE development on China's CO₂ emissions during the operational phase, in which electricity is being generated (Li et al., 2016, Duan et al., 2017, Zhao et al., 2017), and do not capture the impact of NE investments on CO₂ emissions (i.e., emissions resulting from the construction of the NE equipment itself, its transport and installation). An investigation of the impacts of emissions associated with NE investments is important, because China's NE investments totaled \$110 billion in 2015, accounting for more than 33% of the global NE investments of \$329 billion (BNEF, 2016).

The environmental impacts of NE investments in other, developed countries have been analyzed using the input-output (IO) model (Madlener and Koller, 2007, Ritchie and Dowlatabadi, Choi et al., 2014, 2016, Behrens et al., 2016; Median et al., 2016; Yushchenko and Patel, 2016). Nevertheless, in China only one study has been performed. Dai et al., (2016) discussed the environmental co-benefits of NE investments in China to 2050 using a Computable General Equilibrium (CGE) model, concluding that developing NE substantially contributed to carbon reduction. However, their study restricted the analysis to China as a whole, and does not to model the spatial difference of impacts of NE investments on CO₂ emissions between Chinese provinces.

We complement the above literature by presenting a multi-region and multi-period investigation of the emission impacts resulting from NE investments using a multi-region input-output (MRIO) model. Although this study explores how NE investments affected emissions in the past, it can provide policy implications for China's future emission reduction. There was a substantial increase in installed NE capacity in the period under study, so we constructed a counterfactual scenario, in which the NE investments did not take place and were replaced by thermal power in order to satisfy an exogenous electricity demand, following the approach of Behrens et al., (2016). Considering that the NE investments will have a long-term impact on the operational-phase emissions of power generation due to the long lifetime of power plants, we analyze not only the impact of NE investment itself, but compare it with the carbon impact associated with the operational phase of NE generation. We quantify their separate contributions across Chinese provinces. Moreover, we estimate the impact of NE investments from both the intraregional and interregional perspectives. This will better aid us to identify ways to reduce emissions from NE investments.

This paper is organized as follows. Section 2 summarizes previous relevant research. Section 3 describes methods and data sources. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the paper.

2. Literature Review

There are a growing number of studies exploring the environmental implications of investing in NE at national and/or regional level. In our introduction, we showed that CGE and IO models are important tools to do such analysis from a macroeconomic perspective. In contrast to e.g. MARKAL type of models (Cong 2013, Zhang et al., 2016),

and hybrid Life Cycle Assessment (LCA) models (Perera et al., 2013, Hertwich et al., 2015), these approaches model the impact of NE investments by including the interrelationships of the NE sector with all other sectors of the economy.

A CGE model can show how an economy reacts to a change in policy or technology in a dynamic way. However, the method requires abundant data, as cost and economic parameters for various energy technologies are required (Qu et al., 2017). Case studies representing the CGE models are Yahoo and Othman (2017) as well as Yamazaki and Takeda (2017). There is an influential study considering environmental impacts of China's NE investments from Dai et al., (2016), who used a CGE model to estimate how NE investments in China affect employment, economy and emissions. They concluded that the large-scale NE investments would generate a total of approximately 61 Gt CO₂ reductions over the whole period 2010-2050. However, this study focuses on the impacts of a future evolution of NE investments, and thus does not assess the environmental impacts of historical NE investments. Understanding how CO₂ emissions have changed over time due to NE investments is important, as it provides empirical evidence for future policy choices. Furthermore, that study considers only the impacts of NE investments on a national level, and does not provided disaggregated results per province. Although the general consensus is that the development of NE will reduce CO₂ emissions (Dai et al., 2016), it remains unclear how these impacts are distributed within China. This is important because, as case studies of wind investments of Germany shows (Ulrich et al., 2012), the magnitude of NE impacts may differ across regions.

CGE models may not be available for the analysis on multi-regional impact of NE investments in China, as the availability of cross-regional economic data is limited. Multi-Regional IO (MRIO) model has the advantage of representing transactions between several countries/regions and their corresponding economic sectors using readily available data (Hamilton and Kelly, 2017). This makes them suitable for the assessment of cross-national/regional impacts. Additionally, IO is based on actual observations of trade among the sectors and can be used to study the short-term impact of a demand stimulus (Lee et al., 2011). As they are also transparent and computationally straightforward, IO models have been often used in the literature to assess the historical impact of NE investments on CO₂ emissions. In the literature, the economic (Caldes et al., 2009, De Arce et al., 2012, Markaki et al., 2013, Chun et al., 2014, Varela-Vazquez and Sanchez-Carreira, 2015) and employment (Lehr et al., 2008, 2012, Tourkolias and Mirasgedis, 2011, Oliveira et al., 2013, Simas and Pacca, 2014, Ortega et al., 2015, Okkonen and Lehtonen 2016, Dvořák et al., 2017, Hedi, 2017) impacts have drawn the bulk of the attention in NE studies. Although the present paper is focused on environmental impacts, the mechanics of studying different types of impacts are not very different, so there is a strong theoretical background to the model constructed and developed in this work.

Lucchesi et al., (2017) applied an IO model to estimate the environmental impacts of investment changes for different electricity sources in Brazil. Choi et al., (2016) calculated the environmental impacts of a new gasoline tax coupled with bio-subsidy benefits. Median et al., (2016) assessed the environmental benefits of energy efficiency investment in Spain. Behrens et al., (2016) estimated the environmental impact of NE investments over the period 2000-2010 in Portugal. Other studies considering environmental impact illustrate the importance of certain investment activities by evaluating the changes of direct and indirect CO₂ emissions caused by NE investments (Madlener and Koller, 2007, Choi et al., 2014, Ritchie and Dowlatabadi, 2014). The bulk

of literature from China's IO research looks at the jobs and incomes generated from NE investments (Lee et al., 2011, Cai et al., 2014). To the best of our knowledge, no existing IO approach has been used to evaluate the environmental impact of NE investments in China. Moreover, no studies investigate interaction mechanisms about environmental impact of NE investments across regions, especially the interregional spillover effects caused by NE investments.

3. Methods and data

3.1. Methods

3.1.1 Introduction

Following the analysis of Behrens et al., (2016) and Usubiaga et al. (2017), we determine the net emissions resulting from the expansion in NE infrastructure compared against a counterfactual scenario where the expansion did not take place. Here we divide the environmental impacts of the expansion in NE infrastructure into two parts: investment and operational phase. The former accounts for the CO₂ emissions that result from the installation of new NE infrastructure (e.g. construction of wind turbines, transportation to the wind farm and assemblage); the latter accounts for the change of CO₂ emissions associated with structural changes in the China's electricity mix. The counterfactual scenario assumes that new installed capacity of NE and electricity output from the new NE capacity are both replaced by thermal power, but all other settings, including power demand, are the same as in the reference scenario. It is noted that China's thermal power generation indicates a coal-dominated mix of fossil fuels, such as oil and natural gas.

Since we assume that electricity production in both scenarios is the same, the installed capacity (m) and electricity generation (g) of thermal power in the counterfactual scenario is calculated by

$$m_1^{alt} = m_1^{ref} + \sum_{i=2}^5 m_i^{ref} \times \frac{h_i}{h_1} \quad 1(1)$$

$$g_1^{alt} = g_1^{ref} + \sum_{i=2}^5 m_i^{ref} \times h_i \quad 1(2)$$

where index $i=1,...,5$ refers to the various electricity technologies in a specific order: thermal, hydro, nuclear, wind and solar power; m is the amount of new installed capacity; g is the amount of electricity production; h_i is the annual usage hours of NE technology i (equaling to the annual electricity generation of i in kWh divided by its annual installed capacity in kW), h_i/h_1 acts a conversion factor from technology i to thermal power generation to keep the same amount of electricity production between reference and counterfactual scenario. The relative weight of the different technologies in the counterfactual electricity mix is calculated by assuming that the quantity of NE of the preceding year remains constant and thermal power increases as described in Eqs. (1-1) and (1-2).

3.1.2 Additional CO₂ emissions due to NE investments by Chinese region

Two methods are used to estimate the carbon impact of NE investments: one is the process analysis (bottom-up approach), which highlight carbon flows in a series of NE infrastructure processes, and the other is the IO model (top-down approach), which is

rooted in the complete supply chain of economic activity (Crawford et al., 2018). The process analysis, which is relatively straightforward based on process detail, are easier to be understood than IO models. However, the process analysis mostly focuses on the direct emissions, typically neglecting the indirect emissions in more upstream industries (Hondo and Moriizumi, 2017). The IO model is beneficial to access the emissions in the supply chain because it accounts for indirect emissions based on the IO relationships among all sectors in the whole economy. The low resolution of IO tables, however, may give biased results, as emissions data refers the average of sub-products in the broader sector (Zafrilla et al., 2014). For example, if the new demand for solar panels due to investment in solar power is 10 million yuan, we will consider this additional demand to be spread over the outputs of the whole electronic equipment sector. Meanwhile, the additional demand of silicon due to the production of solar panels is distributed among all the inputs that the electronic equipment sector receives from the non-metal material sector along supply chains. Further explorations and similar approaches can be found in Su and Ang, (2010), Matumoto and Hondo, (2011), Wiedmann et al., (2011) and Rocco et al., (2017).

In order to calculate the impact of NE investments on CO₂ emissions in total and by region in China, we employ a multi-regional (MR)IO model which distinguishes interregional and intraregional transactions (Zhang et al., 2013) between 21 sectors in 30 Chinese regions. We quantify the carbon impact of investment specifically in NE infrastructure (e.g. construction of a power plant, and the purchase and installation of equipment). Investments in the general electricity grid, such as large-scale transmission projects and distribution system are not included in the analysis, as neither are the final disposal stage of NE facilities and equipment.

In the basic Leontief model (Eq. (2)) calculates the change in sectoral CO₂ emissions (MtCO₂), Δq , as:

$$\Delta q = BL\Delta y \quad (2)$$

where B is a row vector of CO₂ emission coefficients expressing carbon emissions (MtCO₂) per unit of economic output (million yuan) of each sector; $L = (I - A)^{-1}$ is a Leontief inverse matrix, and in turn A is the matrix of technical coefficients (expressing which inputs from other sectors are required to generate a unit of output of a given sector); and Δy is a vector of an exogenous final demand stimulus, in our case the volume of investments in an electricity technology (e.g. wind, solar).

We use Eq. (2) as a starting point to estimate the carbon impact of NE investments, but because the classification scheme employed in China's MRIO tables does not detail electricity sub-sectors, we follow the method developed by Hedi, (2017). This method requires the quantification of the magnitude of new economic activities associated with NE investments. Δy can be viewed as an exogenous change imposed on the different sectors in the MRIO table. It is defined as $\Delta y = \hat{S}V$, the product of a vector of investment scale (V) of an electricity technology and an diagonal matrix of input share (S) that represents the investment cost structure of given electricity technology. In other words, S is the production recipe of a particular energy technology and V is the total amount of investment in that technology. For example, we consider that the scale of nuclear power investment in a region is v_1 and that the production recipe of nuclear power in a two-sector economy is s_1 and s_2 , respectively. The new demand for products from sector 1 and 2 that results from investment in nuclear power is $\Delta y_1 = \begin{bmatrix} v_1 s_1 \\ v_1 s_2 \end{bmatrix}$. It should be noted

that to better determine the carbon emissions allocated to an investor in NE during a certain period, we use consumption-based accounting to estimate the regional carbon impact of NE investments. The analysis is performed separately for each technology in each region. Thus, the impact of investment in an electricity technology (Δq) in a region is:

$$\Delta q = \hat{B}L\hat{S}\hat{V} \quad (3)$$

MRIO model comprises of n_R regions, each of them with n_S economic sectors. Δq is the resulting matrix of sectoral emissions with side length $n_R n_S$. B is a diagonal matrix of environmental intervention coefficients with side of length $n_R n_S$. L is a square Leontief inverse matrix with side of length $n_R n_S$. To discriminate the impact of NE investment across all regions the investment scale and share matrix are reframed as follows. S is a diagonal input share matrix, expressing the input weights of sectors that exist within the MRIO tables and describing the production recipe of investment in a particular electricity technology; V becomes a diagonal matrix, containing the investment scale (million yuan) in a given electricity technology in a given region whereas other regions are set to zero.

It is important to note that we assume the investment cost structure of an electricity technology, that is, the input share matrix S , for different periods and regions to be identical. The assumption may be considered as reasonable, as in view of the medium term (2002-2010) horizon of this study, the investment cost structure is unlikely to change quickly. Moreover, the technology that meets electricity installation is relatively mature and can be assumed to remain unchanged nationwide (Li et al., 2012). Now, it is possible to quantify two different CO₂ effects associated with the electricity investment. The first is the intraregional effect occurring in the domestic activities of investment, representing one region's CO₂ emissions induced by domestic electricity investments. The second is the interregional spillover effect caused by the production along the supply chain and is calculated through the Leontief inverse matrix. This can be defined as one region's CO₂ emissions induced by another regions' electricity investments. The spillover effect facilitates understanding of how a region's electricity investment impacts other regions' emissions when those regions act as producers of intermediate inputs in domestic supply chains.

In order to make meaningful comparisons across time and regions we do not report carbon intensity values in monetary but in energy terms. That is, we will examine the emissions per unit of installed capacity (MtCO₂/GW), p , defined as:

$$p_{r,i} = \Delta q_{r,i} / m_{r,i} \quad (4)$$

where r is an index referring to one of the 30 provinces and the total net impact of NE investments (Δq_{inv}) is the amount of CO₂ emissions that have been produced in the reference scenario minus the total CO₂ emissions that would have been produced in the counterfactual scenario. For each scenario, CO₂ emissions equal the amount of new installed capacity (m) multiplied by the CO₂ emission coefficient (p). Thus,

$$\Delta q_{inv} = \sum_r \sum_i p_{r,i} \times m_{r,i}^{ref} - \sum_r \sum_i p_{r,i} \times m_{r,i}^{alt} \quad (5)$$

3.1.3 Reduction in operational CO₂ emissions due to expanded NE capacity

The operational emissions from NE are calculated using the theoretical framework developed by Guevara and Rodrigues, (2016), in which an energy-economy sequential

hybrid model is used to combine MRIO model (in which there is a single electricity sector) with more detailed energy data on each particular electricity technology. The vector of direct emission coefficients is now decomposed in four separate terms, with the full Leontief model becoming:

$$q = CFTELy \quad (6)$$

Let n_R the number of regions, n_S be the number of sectors, and n_F be the number of fuel types. y is a column-vector of final demand of length $n_R n_S$, with nonzero values in estimated region and the remaining values empty; E is a matrix with n_R rows and $n_R n_S$ columns, referring to the electricity intensity of each sector in each region (in kWh/yuan); T is the matrix of interregional electricity transmission (Zhang et al., 2017), with $2n_R$ rows (to distinguish production for domestic use and for interregional transmission) and n_R columns, referring to the electricity output that required by itself and regions; F is the fuel use matrix with $2n_R$ columns and $2n_R n_F$ rows, describing to the electricity mix in each region (the factor 2 in the number of rows and columns is required to distinguish electricity production for intraregional consumption and for interregional transmission); finally, C is the carbon emission matrix with n_R rows and $2n_R n_F$ columns, referring to emission intensity of different electricity technologies in each region (in MtCO₂/kWh).

In order to present the Eq.(6) clear we give an example economy with three sectors (s1, s2 and s3, in which s3 is electricity sector), two regions (r1 and r2) and two fuel types (f1 and f2), for which we have a 4×6 carbon coefficient matrix (C), a 6×4 fuel mix matrix (F), a 4×2 electricity transmission matrix (T), a 2×6 electricity intensity matrix (E), a 6×6 Leontief matrix (L) and a 6×1 final demand matrix (Y). The information for C F T E L and Y can be arranged as below

$$C = \begin{vmatrix} C_{f1}^{r1} & C_{f2}^{r1} & & & & \\ & & C_{f1}^{r1} & C_{f2}^{r1} & & \\ & & & & C_{f1}^{r2} & C_{f2}^{r2} \\ & & & & & C_{f1}^{r2} \end{vmatrix} \quad (7(1))$$

$$F = \begin{vmatrix} F_{f1}^{r1} & & & & & \\ F_{f2}^{r1} & & & & & \\ & F_{f1}^{r1} & & & & \\ & F_{f2}^{r1} & & & & \\ & & F_{f1}^{r1} & & & \\ & & F_{f2}^{r1} & & & \\ & & & F_{f1}^{r1} & & \\ & & & F_{f2}^{r1} & & \end{vmatrix} \quad (7(2))$$

$$T = \begin{vmatrix} T^{r1r1} & & T^{r1r1} & & & \\ & T^{r1r2} & & T^{r1r2} & & \\ & T^{r2r2} & & T^{r2r2} & & \\ T^{r2r1} & & T^{r2r1} & & & \end{vmatrix} \quad (7(3))$$

$$E = \begin{vmatrix} E_{s1}^{r1} & E_{s2}^{r1} & 0 & & & \\ & & & E_{s1}^{r2} & E_{s2}^{r2} & 0 \end{vmatrix} \quad (7(4))$$

$$L = \begin{vmatrix} L_{s1s1}^{r1r1} & L_{s1s2}^{r1r1} & 0 & L_{s1s1}^{r1r2} & L_{s1s2}^{r1r2} & 0 \end{vmatrix}$$

$$\begin{vmatrix} L_{s2s1}^{r1r1} & L_{s2s2}^{r1r1} & 0 & L_{s2s1}^{r1r2} & L_{s2s2}^{r1r2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ L_{s1s1}^{r2r1} & L_{s1s2}^{r2r1} & 0 & L_{s1s1}^{r2r2} & L_{s1s2}^{r2r2} & 0 \\ L_{s2s1}^{r2r1} & L_{s2s2}^{r2r1} & 0 & L_{s2s1}^{r2r2} & L_{s2s2}^{r2r2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \quad 7(5)$$

$$Y = \begin{vmatrix} y_{s1}^{r1} \\ y_{s2}^{r1} \\ y_{s3}^{r1} \\ 0 \\ 0 \\ 0 \end{vmatrix} \quad 7(6)$$

Based on Eq. (6), the net operational impact of NE (Δq_{ope}) is quantified as:

$$\Delta q_{ope} = CF^{ref}TELy - CF^{alt}TELy \quad (8)$$

An important difference between the impact of NE investment and operational impact of NE is related to the time frame considered. The impact of investment is localized in a single year (or a few years, if the implementation of the project is complex and has a longer duration), while the operational impact will last throughout the lifetime of the installation. Hence, the operational impact of NE will continue after 2010, and take place over the entire project period (Behrens et al., 2016).

Note that for the purpose of analysis we will not look into the carbon intensity of the operational phase and hence no analogue of Eq. (4) will be developed here. Note also that there are alternative approaches to disaggregating the electricity sector by disaggregating the MRIO table itself (as described by Lindner et al., (2013), Lindner and Guan (2014) and Wang (2017)). However, the disaggregation of the IO table does result in parametric and systematic errors, as there are a range of probability for the unknown technical coefficients of the disaggregate IO table (Wiedmann et al., 2011, Lindner et al., 2012). In order to minimize error in this study, we develop a hybrid system, with a disaggregated power sector in energy units, which generates electricity for the aggregated MRIO electricity sector in monetary units. This is possible because every electron is ‘equal’, that is, all the energy in electrical power generation goes to make the same product. According to this approach, the operational impact of NE can be investigated by calculating the changes in proportions of different energy types to the total energy consumption in the same physical unit.

3.2. Data

The MRIO tables of China’s 30 provinces for 2002, 2007, 2010 are obtained from Shi and Zhang (2012), Liu et al., (2012), and Liu et al., (2014), respectively. The 30 sectors listed in 2007 and 2010 tables and the 21 sectors listed in the 2002 table are aggregated to 21 sectors to have consistent tables for 2002, 2007 and 2010 (as shown in Table A1 in Appendix). Therefore, we work under the supposition that in many cases, the ratio of domestic products and imports during the input of each type of goods to be constant.

We use official data, including the history of cement production and energy and electricity consumption to estimate sectoral CO₂ emissions. We consider emissions from cement production (an emissions-intensive process, Shan et al., 2017) because cement is a major input in the construction of some energy types (very important for hydropower and nuclear, medium importance for wind turbines and low importance for solar). We apply

the IPCC (2006) sectoral approach to estimate CO₂ emissions. CO₂ emissions equal activity data (fossil fuel consumption and cement production) multiplied with carbon emission factors. The activity data of fossil fuels for 2002, 2007 and 2010 are collected from the Provincial Energy Balance Tables reported by *China Energy Statistics Yearbook* (NBS, 2003a, 2008a, 2011a). Because the Provincial Energy Balance Tables of China only released regional fossil fuel consumptions at very aggregated sectoral level, the sub-sectoral fossil fuels consumption refers to Provincial Statistical Yearbooks of China's 30 provinces (NBS, 2003c, 2008c, 2011c). The data of the annual cement production are collected from the *China Statistical Year book* (NBS, 2003b, 2008b, 2011b). Carbon emission factors for fossil fuels (tonne CO₂/ tonnes, m³) and cement production (tonne CO₂/ tonnes) are collected from report of the IPCC (2006) and NDRC (2011). We compare the resulting total Chinese CO₂ emissions in our IO model with numbers from other datasets. Over the three years of our analysis, our emission estimates were 1%-4% lower than those reported in Emissions Database for Global Atmospheric Research (EDGAR), and 10%-15% higher than the Energy Information Administration (EIA), Carbon Dioxide Information Analysis Center (CDIAC) and BP estimates. The agreement across different CO₂ emission accounting approaches gives confidence in the reliability of the aggregated emission estimates.

Electricity investment data comes from the *China Electric Power Yearbook* (CEPYEB, 2003, 2008, 2011) and *Annual development report of China's power sector* (CEC, 2003, 2008, 2011). The investment structure of NE refers to Dai et al., (2016), and the data for thermal power is collected from *Cost and Performance Baseline for Fossil Energy Plants* (National Energy Technology Laboratory, 2010) (see Table A3). The data of electricity capacity and generation are collected from *China Electric Power Yearbook* (CEPYEB, 2003, 2008, 2011). Electricity transmission data for provincial grids in 2007 and 2010 are from the *Annual Report of Power Market Transactions* (SGC, 2008, 2011). Electricity transmission data for provincial grids in 2002 are from CEPYEB (2003).

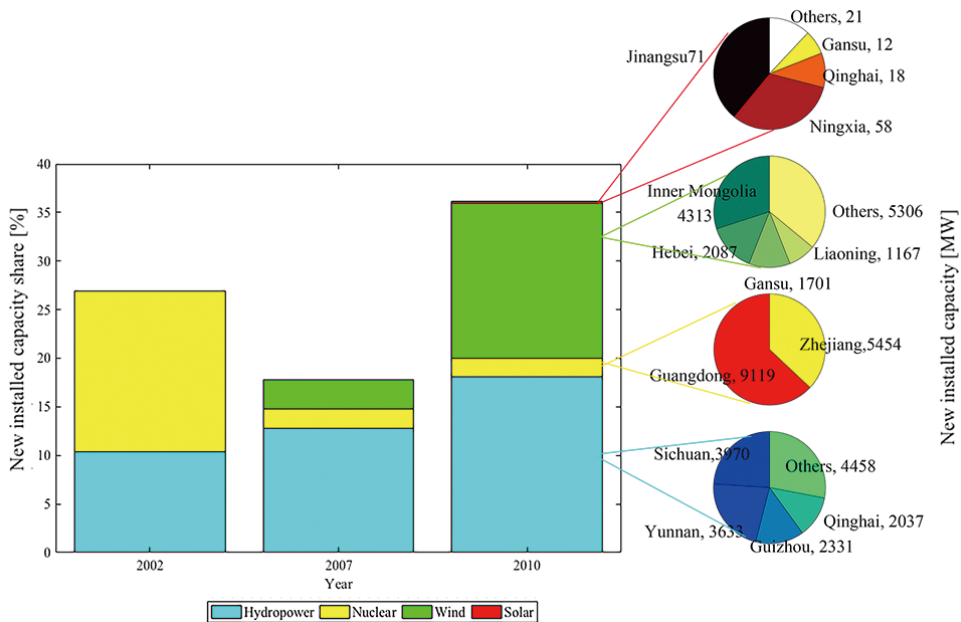


Fig.1. Evolution of China's NE investments.

As illustrated in Fig.1, in 2002, NE comprised 26.9% of total new installed capacity (in MW), with the largest increases in nuclear and hydropower, representing 16.5% and 10.3% of the total respectively. In 2007, the installed capacity of wind power started to increase, amounting to 3.0% of the total. The installed capacity of nuclear power accounted for 2.0% of the total. From 2007 to 2010, the installed capacity of wind power continued to increase at a rapid rate, reaching a peak of 16.0% of the total by 2010. The new installed capacity for hydropower increased by more than 5%. The share of solar power for new installed capacity was only 0.20% of the total in 2010. Fig.1 also shows which provinces most contributed to the new NE capacity in 2010. Sichuan led with new hydropower capacity of 3.97 MW followed by Yunnan 3.63 MW, Guizhou 2.33 MW and Qinghai 2.03 MW. Zhejiang (9.10 MW) and Guangdong (5.45 MW) contributed the most to the new installed capacity of nuclear power. The new capacity of wind power in Inner Mongolia, Hebei, Gansu, and Liaoning was respectively 4.31 MW, 2.09 MW, 1.70 MW and 1.2 MW, accounting for 60% of the total. Over 71% of the new installed capacity for solar power was concentrated in Jiangsu (71kW) and Ningxia (58kW).

4. Results

The presentation of the results as follows. Section 4.1 presents the distribution of CO₂ emissions in China's 30 provinces. Section 4.2 shows the importance of investment impacts when compared to operational impacts in both historical and counterfactual scenarios. Section 4.3 shows how the carbon performance (measured in MtCO₂/GW) of installing different energy types evolved across Chinese regions, and uses this information to assess the investment impact of the observed expansion in NE infrastructure. Section 4.4 closes the results by assessing the role of supply chains in impacts of the observed expansion in NE infrastructure.

4.1. CO₂ emissions in China

According to our emission estimates, in the period from 2002 to 2010, total CO₂ emissions in China increased by 119%, with an absolute increase of 4.88 Gt CO₂ (see Table 1). Between 2002 and 2010, the largest provincial increases were in Shandong, Inner Mongolia, Hebei, Jiangsu and Guangdong, contributing to 10.9%, 7.7%, 7.1%, 6.9% and 6.4% of the overall national growth, respectively. The distribution of province-level emissions developed over time. In 2002, Hebei (318 Mt), Shandong (313 Mt), Guangdong (266 Mt), Jiangsu (258 Mt) and Shanxi (245 Mt) were the largest five provincial CO₂ emitters. Between 2002 and 2007, Henan's emissions increased by 93.4%, and the top five emitters became Shandong (769 Mt), Jiangsu (572 Mt), Guangdong (535 Mt), Hebei (517 Mt), and Henan (432 Mt) by 2007. In 2010, the share in total emissions of Shandong (9.4%), Jiangsu (6.6%) and Guangdong (6.4%) decreased while that of Hebei (7.4%) continued increasing. The combined share of the five major emitters (Shandong, Hebei, Jiangsu, Guangdong and Shanxi) made up 35.7% of total national emissions. Overall, Shandong, Hebei, Jiangsu, Guangdong, Henan and Shanxi held substantial shares of national total emissions, and Inner Mongolia played an increasingly important role.

Table 1. CO₂ emissions and share of national emissions for 30 provinces.

	2002		2007		2010	
	Emissions (CO ₂ Mt)	Emission share (%)	Emissions (CO ₂ Mt)	Emission share (%)	Emissions (CO ₂ Mt)	Emission share (%)
Beijing	86.4	2.1	143.3	1.9	112.9	1.3
Tianjin	75.2	1.8	115.1	1.6	153.3	1.7
Hebei	317.9	7.8	516.9	7.0	663.5	7.4
Shanxi	244.9	6.0	321.4	4.3	518.9	5.8
Inner Mongolia	137.4	3.4	316.4	4.3	511.5	5.7
Liaoning	232.3	5.7	372.0	5.0	469.7	5.2
Jilin	107.5	2.6	181.0	2.4	214.4	2.4
Heilongjiang	136.0	3.3	210.4	2.8	236.1	2.6
Shanghai	137.4	3.4	306.5	4.1	224.8	2.5
Jiangsu	258.3	6.3	571.9	7.7	594.5	6.6
Zhejiang	180.8	4.4	331.1	4.5	370.4	4.1
Anhui	152.5	3.7	210.4	2.8	278.0	3.1
Fujian	78.3	1.9	166.5	2.3	204.7	2.3
Jiangxi	71.5	1.7	133.2	1.8	151.2	1.7
Shandong	313.3	7.7	768.9	10.4	843.0	9.4
Henan	223.6	5.5	432.4	5.8	524.1	5.8
Hubei	161.0	3.9	268.2	3.6	336.2	3.7
Hunan	112.5	2.7	232.9	3.1	266.7	3.0
Guangdong	265.5	6.5	534.5	7.2	576.7	6.4
Guangxi	56.8	1.4	126.6	1.7	155.1	1.7
Hainan	17.2	0.4	23.5	0.3	30.8	0.3
Chongqing	79.1	1.9	90.3	1.2	156.6	1.7
Sichuan	145.9	3.6	210.5	2.8	305.7	3.4
Guizhou	101.0	2.5	173.9	2.4	202.7	2.3
Yunnan	83.3	2.0	158.0	2.1	199.0	2.2
Shaanxi	87.4	2.1	136.7	1.8	229.8	2.6
Gansu	68.5	1.7	108.9	1.5	133.2	1.5
Qinghai	17.2	0.4	25.6	0.3	33.0	0.4
Ningxia	64.6	1.6	68.6	0.9	103.5	1.2
Xinjiang	79.6	1.9	139.5	1.9	171.7	1.9

Total	4093	100	7395	100	8972	100
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4.2. National CO₂ impacts of non-fossil electricity investments

Our study includes emissions from investment and operation of electricity. For the whole country, Fig.2 shows that between 2002 and 2010, the NE investments led to enhanced carbon emissions, but at the same time these investments resulted in a change in electricity mix which reduced emissions in the NE operational phase. NE investments resulted in a growth in emission of 16.21 Mt in 2002, 28.71 Mt in 2007 and 47.29 Mt in 2010, while emission reductions derived from the operational impact of NE were 48.84 Mt in 2002, 81.83 Mt in 2007 and 129.48 Mt in 2010. These are approximately three times larger than the corresponding figures for the investment impacts.

This means that although an expansion in NE infrastructure increases carbon emissions, these increased carbon emissions can be offset by the carbon savings from NE operation in one year. However, our result show that the differences among different NE types while comparing the two impacts. For hydro and nuclear power, the net carbon impact of investments is smaller than the net operational impact in 2002, 2007 and 2010. In 2007, the net carbon impact of wind power investments is larger than its net operational impact, while in 2010, the net carbon impact of wind power investments almost equals to its net operational impact. This is not necessarily surprising. The carbon pay-back period of NE depends on numerous different factors (e.g. output capacity and site conditions). Renewables can pay back their embodied carbon emissions within a year (Haapala and Prempreeda, 2014, Comodi, et al., 2016). For example, Tahara et al., (1997) shows that the carbon payback time of hydropower is less than one year due to smaller carbon emissions from infrastructure. Also, Bush et al., (2014) shows that wind power could spend one year offsetting the carbon emissions from infrastructure at sites with high wind speeds. Moreover, the higher the output capacity, the shorter the payback period (Atse et al., 2016). Thus, the carbon payback time could be reduced as the capacity of wind power increases.

Moreover, because MRIO tables are only available for 2002, 2007 and 2010 during 2002-2010, we only estimate the carbon impact of NE investments for those specific three years. Although we do not present an evolution of the carbon impact of NE investment in every year, our results still reflect the trend over that period. Thus, due to data availability we use a single year as input for all aspects of the data required in the calculations. This means that each year represents a snapshot of the investment emissions of that year, which for a very dynamic subject such as China's expansion of NE may lead to biases. For example, in a given year the additional electricity output compared to the previous year does not necessarily reflect the new installed capacity in that single year, but will include power from installations that went online in the previous year and will not take into account the power of installations concluded late in the civil year that will only go online in the following year. Furthermore, a project might take longer than a year to complete, which means that investment operations will be spread over several years. Thus, our underlying working assumption is that all year-on-year evolution is smooth, with under-estimations from factors taking place in the preceding year being compensated by factors over-estimated because they take place in the following year.

In contrast, the operational impact will manifest throughout the life time of the installation, so the carbon benefits are primarily received by society during the operation phase of NE projects. This is because investments in electricity infrastructure have long operational

lifetimes, so past investment decisions in China continue to shape electricity mix well into the future, with the total emission reductions due to the substituting thermal power generation lasting throughout the lifetime of the NE power project. For example, currently, the average service life of a solar power project is more than 20 years, thus a solar power plant constructed in 2002 will lock in patterns of Chinese electricity output and affect emissions until 2022.

In 2002, the largest impact in investment was from nuclear power at more than 60% of the total impact of investment. Since 2007, the positive impact of investments in hydropower and nuclear decreased significantly, and their share in the total reduced to 21% and 8% by 2010 respectively. The positive impact of wind investment presented significant growth trend over the period growing to almost 70% of the total by 2010. The result of this is that wind power investment had the largest net contribution to emission growth between 2007 and 2010. The positive impact of solar investment in 2010 was small, accounting for only 1.5% of the total.

From 2002 to 2010, the operational impact of hydropower was in a dominant position, although its proportion of the total impact decreased from 77 % in 2007 to 53% in 2010. Between 2002 and 2010, the operational impact of nuclear power also played a vital role in reducing CO₂ emissions, resulting in a CO₂ emission reduction of 21.48 Mt in 2002, 17.53 Mt in 2007 and 23.46 Mt in 2010. The emission reductions resulting from the operational impact of wind power mainly took place in 2007 (1.24 Mt) and 2010 (37.30 Mt). In 2010, the operational impact of solar power yielded small CO₂ emission reductions (0.08 Mt).

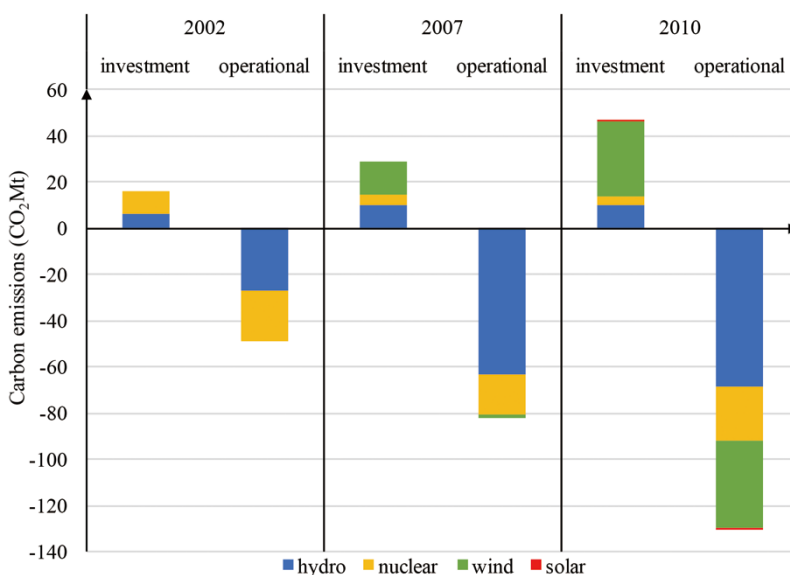


Fig.2. Net investment and operational impacts of NE.

4.3. Regional CO₂ impacts of non-fossil electricity investments

We start the analysis by examining the carbon intensity of capacity installed in energy infrastructure, that is the emissions per capacity installed of different energy types (in

Mt/GW installed). This can then be applied to look at the difference in carbon impacts introduced by NE technologies over the whole lifetime. The MRIO model allows differentiating carbon intensity of installation by province.

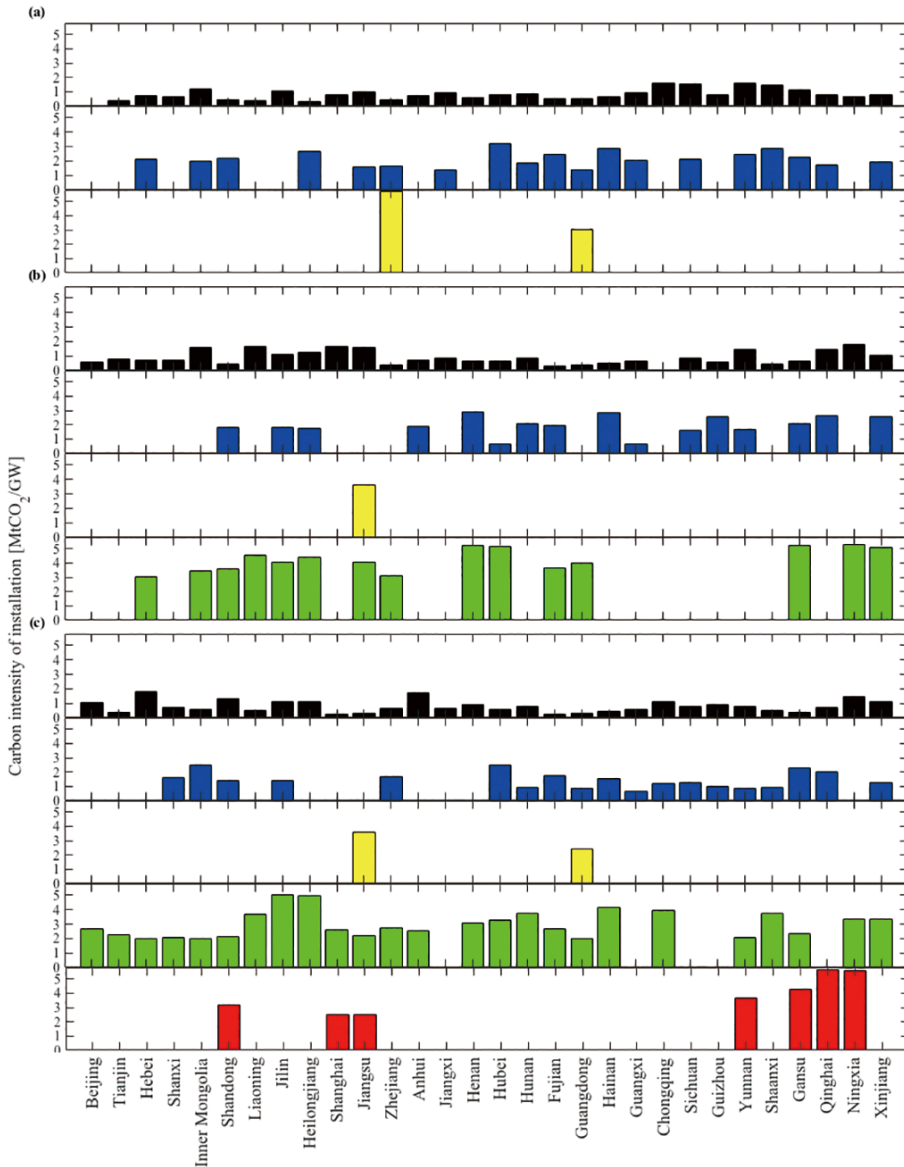


Fig.3. Carbon intensity of installation for various energy types in 30 provinces. Carbon intensity includes all emissions along supply chains which are allocated to the province of installation.

Fig.3 shows the carbon intensity of installation of different energy types in 30 provinces for 2002, 2007 and 2010. The carbon intensity of installation for hydropower in the southwestern region decreased continuously. A significant decrease in the amounts per

unit can be seen from Guangxi and Sichuan. In 2002 the hydropower in Guangxi and Sichuan were 2.04 Mt/GW and 2.13 Mt/GW, respectively, while in 2010 those were only 0.67 Mt/GW and 1.00 Mt/GW. Notably, the carbon intensity of installation for wind in the northern region decreased during 2007-2010. The most significant decreases in the carbon intensity of installation for wind power were in Hebei and Inner Mongolia. In 2007 a 1 GW increase in the investment of wind power led to an additional 6.01 Mt and 5.48 Mt of CO₂ emissions in Hebei and Inner Mongolia respectively, while the same 1 GW allocated to wind power generated only 1.97 Mt and 1.98 Mt of additional emissions. The reason may be the lower investment cost of hydropower and wind power in the southwestern and northern regions due to local advantageous NE development conditions. Additionally, a possible explanation might be that there is a scale effect, with the investment cost of hydropower and wind power in these provinces dropping due to a significant cumulative installed capacity (Zou et al., 2016): In 2010, the installed capacity of hydropower in Guangxi and Hunan was 11 and 31 GW, respectively, representing more than 21% of the whole country's total, and the wind power capacity in Hebei and Inner Mongolia reached 8 GW, which accounted for 29% of the national total (CEC, 2011). Moreover, although provinces with large solar potential capacity are concentrated in northwestern region, the carbon intensity of installation for solar power in the northwestern region are relatively larger than those of eastern region.

The counterfactual scenario assumes that the new installed capacity of NE would be replaced by thermal power, with the same total electricity production described in the historical scenario. Because our assessment is performed on various provinces, we can highlight the spatial heterogeneity across China. Fig.4 shows the net investment and operational impacts of NE, and compares their differences from provincial perspective. We divide China's 30 provinces into eight larger regions, as shown in Table A2 in Appendix. In general, for each province, the net impact of NE investments was positive, while the net operational impact of NE appeared to be negative. This suggests that the carbon impact of NE investments should not be ignored.

In 2002, Zhejiang had the highest net impact of NE investments, accounting for 47.7% of the total. Furthermore, the magnitude of net impacts of NE investments in Zhejiang (7.74 Mt) was larger than that of net operational impact of NE (-5.20 Mt). In 2010, the net impact of NE investments in Zhejiang decreased to 1.83 Mt, while the magnitude of net operational impact of NE grew to -8.65 Mt. This implies that the increased emissions from NE infrastructure has been offset by the emission reductions from NE operation in Zhejiang. Moreover, the magnitude of net impacts of NE investments in other eastern provinces (Shanghai and Jiangsu) were lower than that of net operational impacts of NE during 2002-2010. Hence, the deployment of NE will provide continuous reduction of CO₂ emissions to the eastern region over the life of the investment though increased emissions from NE investments does eat into these savings.

Guangdong played the most significant role in the sharp rise in the net operational impact of NE, accounting for 37.8% of the total operational impact of NE in 2002. In 2007, the magnitude of net operational impact of NE decreased to -15.17 Mt, and then expanded to -32.15 Mt in 2010. Compared to the operational impact of NE, NE investments in Guangdong had relatively small net effects on emissions from 2002 to 2010. These results indicate that NE development in Guangdong has yielded larger emission savings, though the negative operational impact of NE alone is not the complete carbon impact of NE expansion.

In 2002, the southwestern region had a higher net impact of NE investments, given the regions' hydropower development, accounting for more than 20% of the total net impact of NE investments. The trend in the net impact of NE investments for the southwestern region was on the rise between 2002 and 2007. Compared to 2002, the net impact of NE investments in the southwestern region increased by 69.31% in 2007. Specifically, compared to 2002, Sichuan had the largest increase in the net impact of NE investments by 2007 (877%), followed by Guangxi (655%) and Yunnan (379%). Between 2007 and 2010, the total net impact of NE investments in the southwestern region followed a declining trend, reducing by 16.4% in 2010 (6.78 Mt) compared to that in 2007 (5.67 Mt). Specifically, the net impact of NE investments in Guangxi reduced the quickest, decreasing by 84.9% from 2007 to 2010. The net impact of NE investments in Yunnan and Sichuan also reduced sharply, decreasing by 11.5% and 50.7% from 2007 to 2010 respectively. At the absolute level, the net operational impact of NE in the southwestern region had a tendency to increase from 2002 (-13.6 Mt) to 2010 (-28.4 Mt). Specifically, the net operational impact of NE in Sichuan and Yunnan increased the most markedly, increasing by 121% and 125% from 2002 to 2010 respectively. By 2010, the magnitude of net impacts of NE investments in all southwestern provinces was significantly smaller than that of net operational impact of NE.

The net impact of NE investments in the northern, northwestern and northeastern regions maintained an increasing trend from 2000 to 2010. Specifically, the province with fastest growing net impact of NE investments was Inner Mongolia, followed by Gansu, Jilin, Liaoning, Hebei and Shandong. For the northern, northwestern and northeastern regions, the magnitude of net operational impact of NE also experienced substantial expansion during 2002-2010. Specifically, the province with the fastest growing net operational impact of NE was Hebei, whose magnitude of net operational impact of NE expanded to -7.94 Mt CO₂ in 2010 from -0.21 Mt in 2002, followed by Jilin, Inner Mongolia, Shandong, Liaoning and Qinghai. However, between 2007 and 2010, the magnitude of net impact of NE investments for Inner Mongolia and Gansu was considerably larger than that of net operational impact of NE. This means that the key to developing NE in Inner Mongolia and Gansu is paying more attention to managing CO₂ impacts of NE infrastructure.

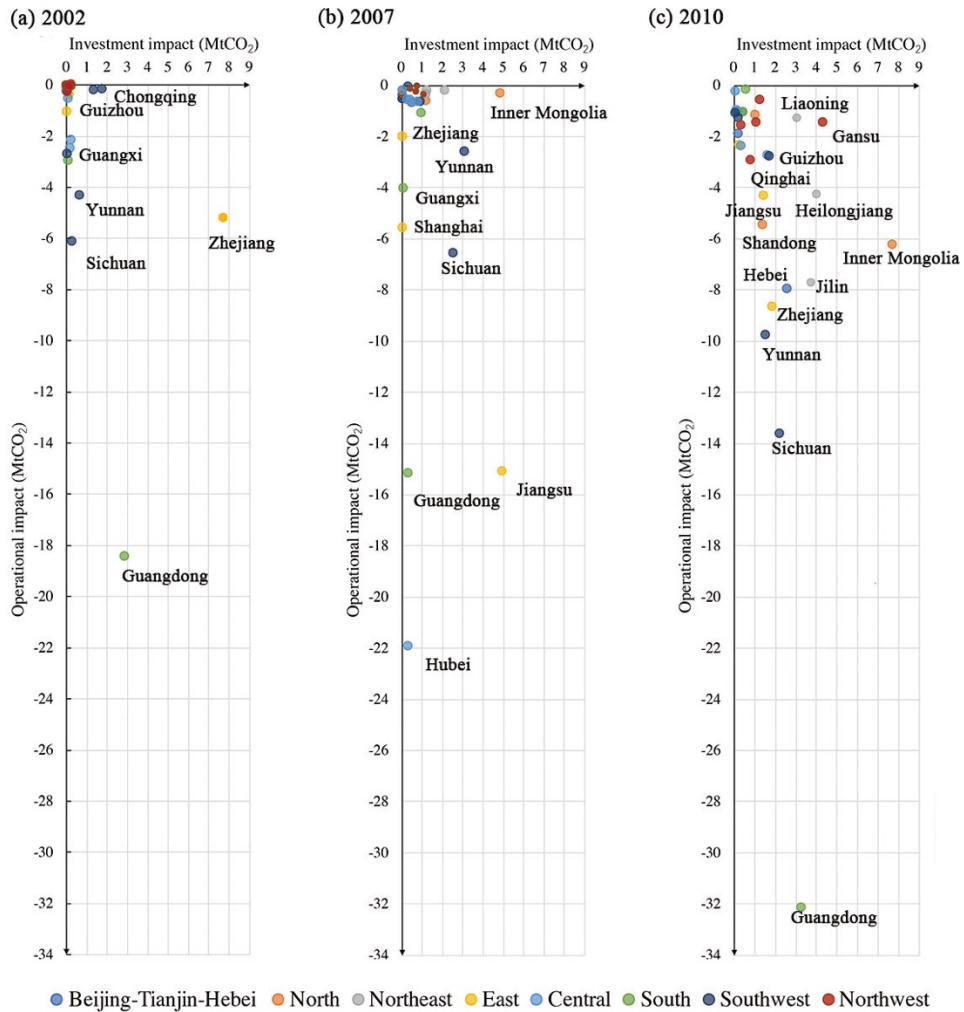


Fig.4. Comparison of net CO₂ impacts between investment and operation.

To better understand the net impact of NE investments by different types of NE, Fig.5 splits the net impact of NE investments and operational impact of NE in 30 provinces for 2010 into NE technologies. The net impact of NE investments fully reflects the geographic distribution of NE resources in China. Hydropower investment was an essential cause of emission growth in the southwestern and central regions, the most significant of which were in Sichuan and Guizhou, bringing a net CO₂ increase of 2.22 Mt and 1.69 Mt respectively. Hydropower operation led to the largest reduction in emissions in Guangdong (-16.95 Mt), followed by Sichuan (-13.35 Mt) and Yunnan (-9.37 Mt). Nuclear power investment had positive effects on emissions in Zhejiang and Guangdong, leading to 1.76 Mt and 2.11 Mt of emission growth respectively. The operational impact of nuclear power played the important role in the decrease in emissions of Zhejiang and Guangdong, resulting in a 5.82 Mt and 13.86 Mt of emission growth respectively.

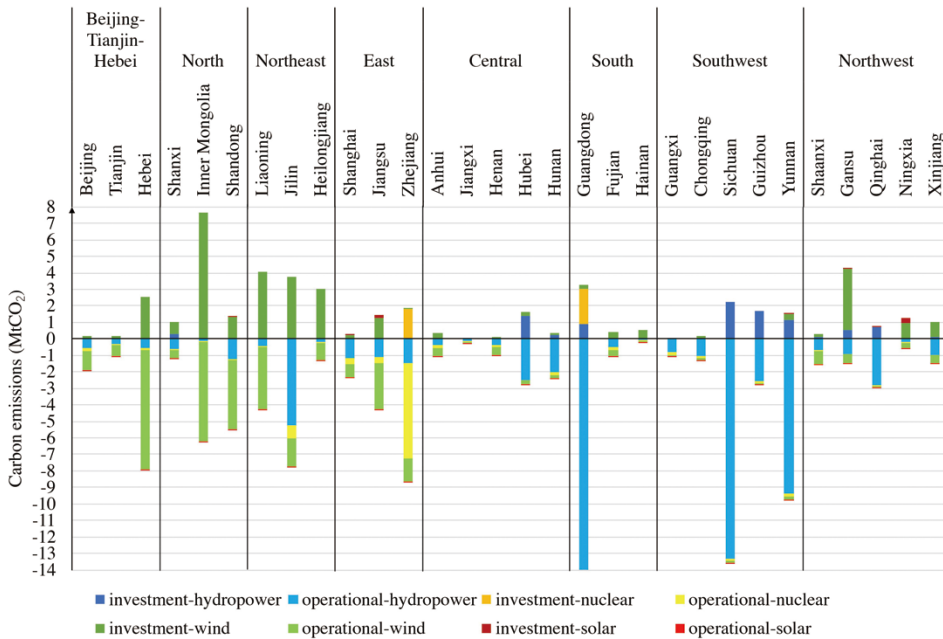


Fig.5. Net investment and operational CO₂ impacts of NE for various energy types in 2010. Note: the net operational impact of NE in Guangdong is significant larger than other provinces. In order to present results more clearly, we set axis y only from 8 to -14. The total net operational impact of NE in Guangdong was -32.15 Mt. The net operational impact of hydropower, nuclear, wind and solar was -16.95 Mt, -13.86 Mt, -1.34 Mt and 0.00 Mt respectively.

Wind power investment had significant net impacts on increase in emissions in Beijing-Tianjin-Hebei, northern, northeastern and northwestern regions. Specifically, wind investment induced the largest increase in emissions in the Inner Mongolia (7.64 Mt), amounting to 99.6% of its total net impact of NE investments. At the same time, the wind power operation had significant net effects on emission reductions in the Beijing-Tianjin-Hebei, northern, northeastern and northwestern regions, the most significant of which was Hebei (-7.24 Mt). Additionally, the magnitude of net impacts of wind power investments outweighed that of net operational impact in several provinces. For instance, in Inner Mongolia and Gansu, the operational impact of wind power led to a net CO₂ decrease of 6.04 Mt and 0.53 Mt respectively, while the wind power investment resulted in a net CO₂ emission increase of 7.64 Mt and 3.73 Mt respectively.

The solar power investment resulted in a net increase of CO₂ emissions in the northwestern and eastern regions. Specifically, the province with the largest net impact of solar power investment in 2010 was Ningxia, followed by Qinghai and Jiangsu. The percentage of net impact of solar power investment compared with the total net impact of NE investments in these provinces was more than 8%. The net decreases due to solar power operation were smaller than the net increases due to solar power investment in Jiangsu and Ningxia. These results show that controlling impacts of solar investment in northwestern and eastern regions is needed to reduce emissions.

4.4. Spillover effects of non-fossil electricity investments

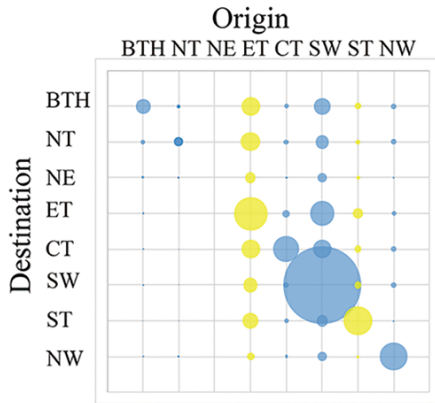
The previous section describes how changes in NE investments impact regional emissions growth. This section investigates the spillover effects of NE investments on regional emissions. Fig.6 shows that from 2002 to 2007, the regions with a relatively high net spillover effect lie mainly in the eastern and southwestern regions. This is because NE investments (especially for hydropower and nuclear) in these two regions are larger from 2002 to 2007, and so require more intermediate goods from other provinces. NE investments in the eastern region increased emissions in all other regions, particularly those of the Beijing-Tianjin-Hebei and northern regions. This reflects the fact that NE infrastructure in the eastern region tends to use more intermediate goods provided by the two regions. The transfer of impact of NE investments from east to Beijing-Tianjin-Hebei and northern regions is appropriate regarding geographic spatial distribution. Moreover, Beijing-Tianjin-Hebei and northern regions have close economic relationships with the eastern region. Their sectors follow the upstream sectors of the eastern region, and large-scale demand of the eastern region provide the primary market for their products.

NE investments in the southwestern region mainly increased intraregional emissions. The reason is that this region is China's primary sources of natural resources, and many manufacturing industries are concentrated there. This naturally makes them use more domestic products (i.e., from the same region) to support NE infrastructure, and thus produce more intraregional emissions. The southwestern region transfers impact of NE investments to the eastern region. This means that NE investments in the southwestern region depend heavily on intermediate inputs from the eastern region. The southwestern region also transferred large impacts of NE investments to the central region, as the southwestern region is geographically close to the central region.

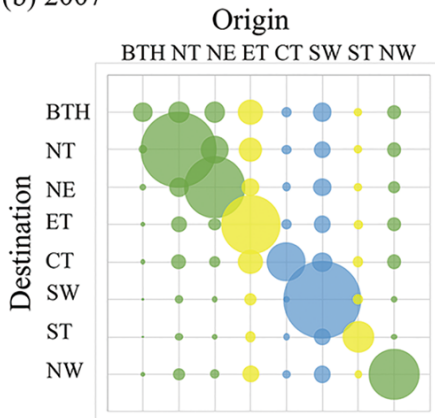
The net spillover effects of NE investments for northern and northeastern regions maintained an increasing trend during 2002-2007 because of the growth of wind power investment. NE investments in the northeastern region had significant spillover effects on emission increases in the Beijing-Tianjin-Hebei and northern regions, as Beijing-Tianjin-Hebei, northern and northeastern regions are geographically connected. NE investments in the northern region also tends to purchase much more goods from its neighbor regions, thus, NE investments in the northern region drove emission increases in the Beijing-Tianjin-Hebei and northeastern regions.

With the rapid growth of wind power investment, the net spillover impact of NE investments in northeastern and northwestern regions increased nearly 3 times from 2007 to 2010. NE investments in northeastern region had a large spillover effect on emissions in the northwestern region, as the northwestern region mainly focused on traditional manufacturing industries and can provide strong support for NE infrastructure. Moreover, NE investments in the northwestern region gave large spillover effects to Beijing-Tianjin-Hebei, northern and central regions.

(a) 2002



(b) 2007



(c) 2010

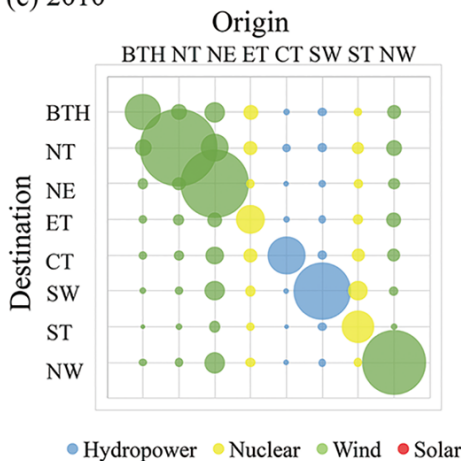


Fig.6. Net spillover effect of NE investments. Note: “Origin” indicates the region that externally influences other regions through its NE investment activities; “destination” indicates the region influenced by other regions’ NE investments. Intraregional effect is shown in the diagonal, while interregional spillover effect is shown in the off-diagonal. The most important NE type in one region is indicated with corresponding colored bubbles.

5. Discussion

In this work, we applied MRIO models to account for the impacts of NE investments and operation in China's 30 provinces. The results showed a positive effect of NE investment and a negative operational effect of NE. Referring to each province, impacts of NE investments and operations were different. The magnitude of net operational impact of NE in all southwestern and eastern provinces has been smaller than that of net impact of investments. Thus, southwestern and eastern regions could expand NE investments to reduce emissions. In their electricity system, the majority of investment impact is from hydropower and nuclear power. Hence, in order to maximize emission savings of NE development, the significant impact of expansion in hydropower and nuclear on reducing China's emissions should be worthy of attention in the long term. The impact of NE investments is significant for northern, northeastern and northwestern regions, so that the magnitude of net operational impact for NE in several provinces (e.g. Gansu and Inner Mongolia) was smaller than that of net impact of investments. This is because the infrastructure of solar and wind power increased demand for manufacturing and construction sectors in northern, northeastern and northwestern provinces. Reducing emissions across the supply chain of the wind and solar power infrastructure may be effective to improve the total carbon impact of NE systems.

To reduce the impact of NE investments on emission increases and implement a targeted regional NE investments policy in China, identifying the pattern for carbon impacts of NE investments appears to be particularly critical. Our analysis shows that because inland regions use more domestic products, the intraregional effect of NE investments in these regions are large. Furthermore, a large spillover effect can be observed in the coastal eastern region, as this region located in the downstream of supply chains with large pulling effects on the production of inland regions. In fact, the meaning of "the spillover effect of NE investments" is similar to that of "spillover of carbon emissions" developed by Meng et al., (2013). From the perspective of supply chains, if a region's NE infrastructure uses more domestic products, the intraregional effect could be larger. However, if this region consumes more intermediate goods from other regions, the interregional spillover effects should be larger. Therefore, the pattern of regional impact of NE investments depends on participation degree in supply chains.

The interregional transfer of impact of NE investments is related to specific geographical location. The impact of NE investments tends to be transferred to neighbor regions, explaining the inflow of impact of NE investments in the central region from the southwestern region. The findings also support the result that NE investments in northern and northeastern regions both have obvious carbon effect on Beijing-Tianjin-Hebei. This means that carbon impacts of NE investments have an evident geographic concentration, which are mainly distributed in the surrounding area with large-scale NE investments. Thus, spatial relationships could be a concern in policy-making for NE development. These findings show partial similarity to works of Yan et al., (2017) and Meng et al., (2017). Feng et al., (2014)'s studies provide a possible explanation for this transfer between neighboring regions, though they only focused on the spatial distribution characteristics of China's carbon emissions. They suggest that since most products are homogenized and do not require long-distance transport, a region tends to use more intermediate goods from adjacent regions considering transportation costs, thus transfers more emissions to neighboring regions. Similarly, NE infrastructure in a province will

induce a large amount of emissions in its surrounding regions by importing intermediate products, particularly those not appropriate for long distance transportation.

Moreover, it is well known that China is a country with large economic diversity between regions. Generally, developing regions (e.g. north, northwest, northeast, southwest) have larger intraregional effects, while developed regions (e.g. east and Beijing-Tianjin-Hebei) show larger interregional spillover effects. Therefore, like the interregional transfer of CO₂ (Liu et al., 2015), the major pattern for spillover effects of NE investments is from developed regions to developing regions. This reflects that developing regions play an important role in supplying energy and raw materials in the supply chains of NE infrastructure. One of the reasons is that manufacturing industries are distributed throughout developing regions, which is used to satisfy input requirements for NE infrastructure. Since manufacturing and construction industries contribute the most to NE infrastructure, from the point of view of production, improving technology and energy efficiency of manufacturing and construction industries in developing regions would be conducive to alleviating the carbon impact of NE investments.

The important interregional transfers of carbon impact of NE investments also included those transferred from northeast to Beijing-Tianjin-Hebei and those from southwest to east. This provides evidences of another pattern of spillover effects: NE investments in developing regions also can affect developed regions' emissions. This is because that the intermediate products utilized for NE infrastructure generally require higher levels of technology, and developed regions can provide such intermediate products. Thus, one possible approach for developing regions to reduce its carbon impact of NE investments is to strengthen interregional collaboration with developed regions and promote technology transfers.

Our methodological framework, which combined with MRIO model to estimate the carbon impacts of NE investments, provides robust arguments for the discussion about the preferable investment pattern of electricity system. However, some limitation of the present work should be mentioned. First, we discussed the possibility of carbon intensity of installation showing that the reduction of carbon intensity of installation may help to weaken the positive impacts of NE investments on emissions. Thus, future extensions could give more insights into the ex-ante projections of carbon impact of NE investments. Second, constrained by investment size of solar power during the period 2002-2010, its CO₂ emission impact was small. In fact, solar power investment increased considerably between 2011 and 2016, so that its impact on CO₂ emissions may be different from our estimated result. However, due to limited data, we did not analyze solar power investment after 2010. The issue of how CO₂ emissions interact with solar power investment needs to be further studied referring to our case studies. Third, it should be noted that, in this study, due to data limitations, we only consider emissions from fossil fuel combustion and cement production, as previous literature highlights the contribution of fossil fuel and cement production to carbon impacts of NE infrastructure. However, as shown in the study by Wiedmann et al. (2011), to further assess the impact of NE infrastructure, emissions from plastics should be included in future work.

6. Conclusions

The recent trend toward developing NE has increased the concern that it will have a large impact on carbon emissions, especially given the large-scale NE investments in China.

Thus, we can wonder whether NE investments have influenced China's carbon emissions at provincial level. With the support of MRIO models, this study implemented a counterfactual scenario of "without NE investments" as the comparative baseline to estimate the carbon impacts of NE investments and operational impacts of NE in 30 provinces between 2002 and 2010. Moreover, we distinguish the intraregional and interregional spillover impacts of NE investments.

By comparing historical emissions and counterfactual scenario, the results confirmed that NE investments drove up CO₂ emissions during 2002-2010, with a net increase of 16.21 Mt in 2002, 28.71 Mt in 2007 and 46.29 Mt in 2010. However, the total operational impact of NE played an important role in mitigating CO₂ emissions in China across the studied periods. The net CO₂ emission decreases in 2002, 2007 and 2010 reached 48.84 Mt, 81.83 Mt and 129.48 Mt. The investment in hydropower and nuclear played relatively larger effects on CO₂ emission during 2002-2007, especially in Guangdong, eastern and southwestern provinces. The magnitude of net impacts of NE investments in these provinces has been smaller than that of net operational impact of NE. This shows the mitigation potential of hydropower and nuclear development. The wind power investment had larger impact on CO₂ emissions during 2007-2010, especially in the northern, northeastern and northwestern regions. However, the net emission reductions from NE operation were offset by the net emission increases from NE investments in several northern, northeastern and northwestern provinces (e.g. Gansu and Inner Mongolia). Significant differences between the intraregional and interregional spillover effects arising from different regions were observed. The developed eastern region has a larger interregional spillover effect, while developing regions, such as southwest, north, northeast and northwest, show larger intraregional effects. Moreover, the regions with large-scale NE investments tend to transfer a large carbon impact of NE investments to neighboring regions.

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Appendix

Table A1. Sector classifications for the Chinese economy.

Code	Sector
AGR	Agriculture
MC	Mining
FD	Food
TEX	Textile
TF	Processing of Timber and Furniture
PP	Paper and Paper Products
PC	Petroleum Refining and Coking
CHE	Chemical
NMP	Non-metallic Mineral Products
SPM	Smelting and Pressing of Metals
MP	Metal Products
GE	General Equipment
TE	Transport Equipment
EME	Electric Machinery and Equipment
EE	Electronic Equipment
IM	Instruments and Machinery of Cultural Activity and Office Work
OM	Other Manufacturing
ELE	Electricity
CON	Construction
TRA	Transportation
SE	Services

Table A2. Region classifications.

Region	Province that included in each region
Beijing-Tianjin-Hebei (BTH)	Beijing, Tianjin and Hebei
North (NT)	Hebei, Shanxi, Inner Mongolia and Shandong
Northeast (NE)	Liaoning, Jilin and Heilongjiang
East (ET)	Jiangsu, Shanghai and Zhejiang
Central (CT)	Henan, Anhui, Hunan, Hubei and Jiangxi
South (ST)	Fujian, Guangdong and Hainan
Southwest (SW)	Sichuan, Chongqing, Guizhou, Yunnan and Guangxi
Northwest (NW)	Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang

Table A3. Investment structure of electricity technologies (%).

Sector	Thermal	Hydro	Nuclear	Wind	Solar
AGR	0	0	0	0	0
MC	0	0	0	0	0
FD	0	0	0	0	0
TEX	0	0	0	0	0
TF	0	0	0	0	0
PP	0	0	0	0	0
PC	0	0	0	0	0
CHE	0	0	0	0	0
NMP	0	0	0	0	0
SPM	0	0	0	0	0
MP	0	0	0	5	3
GE	29	28	55	38	40
TE	0	2	0	5	0
EME	0	0	0	0	0
EE	4	7	15	5	12

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IM	0	0	0	0	0
OM	0	0	0	0	0
ELE	0	0	0	0	0
CON	55	35	25	15	13
TRA	6	8	0	12	8
SE	6	20	5	20	24
Total	100	100	100	100	100

Table A4. Regional carbon intensity of electricity installation (MtCO₂/GW).

	thermal			hydro			nuclear			wind		solar
	200 2	200 7	201 0	200 2	200 7	201 0	200 2	200 7	201 0	200 7	201 0	201 0
Beijing		0.59	1.07								2.65	
Tianjin	0.36	0.80	0.39								2.27	
Hebei	0.70	0.70	1.77	2.12						3.01	1.97	
Shanxi	0.68	0.71	0.73			1.60					2.08	
Inner Mongolia	1.20	1.56	0.59	2.00		2.47				3.48	1.98	
Shandong	0.47	0.44	1.33	2.18	1.77	1.38				3.55	2.10	3.20
Liaoning	0.36	1.64	0.52							4.55	3.67	
Jilin	1.08	1.14	1.13		1.82	1.39				4.08	5.03	
Heilongjiang	0.31	1.26	1.10	2.67	1.75					4.38	4.98	
Shanghai	0.79	1.67	0.24								2.61	2.48
Jiangsu	0.99	1.61	0.29	1.58			3.62			4.07	2.19	2.50
Zhejiang	0.41	0.37	0.65	1.62		1.70	5.71		3.56	3.07	2.76	
Anhui	0.74	0.73	1.70		1.86						2.54	
Jiangxi	0.89	0.84	0.64	1.38								
Henan	0.61	0.66	0.88		2.87					5.21	3.04	
Hubei	0.81	0.62	0.57	3.21	0.66	2.47				5.13	3.30	
Hunan	0.86	0.87	0.79	1.83	2.08	0.89					3.76	
Fujian	0.50	0.31	0.22	2.46	1.97	1.75				3.67	2.69	
Guangdong	0.50	0.38	0.32	1.42		0.89	3.07		2.44	3.99	2.00	
Hainan	0.62	0.52	0.41	2.86	2.85	1.54					4.13	
Guangxi	0.94	0.64	0.60	2.04	0.65	0.67						
Chongqing	1.60		1.09			1.19					3.95	
Sichuan	1.56	0.82	0.74	2.13	1.58	1.26						
Guizhou	0.78	0.60	0.91		2.56	1.00						
Yunnan	1.60	1.42	0.78	2.46	1.66	0.84					2.05	3.67
Shaanxi	1.44	0.43	0.51	2.84		0.90					3.77	
Gansu	1.09	0.65	0.38	2.26	2.11	2.29				5.21	2.30	4.27
Qinghai	0.80	1.46	0.72	1.69	2.59	2.00						5.64
Ningxia	0.68	1.78	1.43							5.25	3.33	5.54
Xinjiang	0.77	1.04	1.11	1.93	2.53	1.24				5.05	3.32	

Chapter 5

Carbon overhead: the impact of the expansion in low-carbon electricity in China 2015-2040

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Submitted to Energy Policy on January 2018, accepted

Abstract

China has embarked on a massive program of low-carbon electricity (LE) deployment, in order to reduce its current dependence on coal. The cumulative installed capacity of LE in 2015 was almost four times of that in 2002. Moreover, China has a target of 20% for non-fossil fuels in primary energy consumption by 2030. LE provides substantial carbon savings in the use phase, but LE infrastructure tends to require more materials than their fossil-fuel electricity counterpart. Here we estimate the carbon ‘overhead’ from infrastructure expansion during China’s transition to LE. We report estimates of the learning curves of the carbon intensity of LE installation, calculated from regional historical data in the period 2002-2012. We combine this information with the predicted cumulative installed capacity from well-known scenarios from national and international bodies. We then project the trends of carbon impacts from LE investments up to 2040. Our results show that, under all scenarios and every year, the annual carbon impact of LE investments never exceeds 4% of China’s total carbon emissions, and that the carbon impacts of the expansion in LE infrastructure show either a steady decline or a peak during 2030-2035 before declining further.

Keywords: CO₂ emissions; low-carbon electricity technology; investment

1. Introduction

1.1. The importance of low-carbon electricity development

Along with high-speed economic development, China is facing a growing pressure to address increasing carbon emissions (Li et al., 2016). China’s total carbon emissions between 1996 and 2013 increased by 219%, with an absolute growth of 6563 Mt (Ye et al., 2017). Currently, China is the largest CO₂ emitter in the world (Liu et al., 2013). Increasing emissions result mainly from an over-dependence on fossil fuels (Wang et al., 2016). In the 14 years between 2002 and 2016, China’s electricity generation increased by 264%, with thermal power accounting for around 75% of this growth (CEC, 2017). In order to accommodate future expansion in electricity generation while mitigating carbon emissions, the expansion of low-carbon electricity (LE) became a key focus of China’s policy initiatives (He, 2015). The 13th Five-Year Plan proposes specific targets by 2020 of: 340 GW hydropower, 58 GW nuclear power, 210 GW wind power and 110 GW solar power (NEA, 2016). China also promised to increase the share of non-fossil fuels in primary energy consumption to approximately 20% by 2030 (GOV.CN, 2015). This means that China is likely to experience changes in its electricity mix that will result in a high share of LE, and decreasing carbon emissions in the future. Given the scale of these changes, the impact of this increasing LE share needs a robust assessment.

1.2. Current status and future prospects of low-carbon electricity

Although thermal power is still a key component of China's electricity mix, the share of LE in total installed capacity has steadily increased. Figures 1 (a) and (b) show that the cumulative installed capacity of thermal power in China increased by 286% from 2002 to 2015, while the cumulative installed capacity of LE in 2015 was almost four times of that in 2002. Hydropower increased from 86 GW to 320 GW between 2002 and 2015. Nuclear power increased by 6% in the same period, reaching 29 GW in 2015. Since 2007, wind power grew rapidly with an average annual growth of 53% during 2007-2015, reaching 129 GW by 2015. The annual growth rate for solar power varied between 79-200% during 2010-2015. In absolute figures, solar power increased from 1 GW in 2010 to 77 GW in 2015.

Given the fast growth of China's LE, much attention has been focused on long-term scenarios for LE development. The International Energy Agency (IEA, 2017, 2016, 2014) reports three scenarios for LE installation in China, assuming Current Policies (IEA-Current), New Policies (IEA-New) and Sustainable Development Policies (IEA-Sustainable). There are also national scenarios developed by the National Development and Reform Commission for High Renewable Energy Penetration (NDRC-High RE) (NDRC, 2015), see Figure 3 (c) and (d). Both these national and international produced scenarios project changes to 2040. By 2040, the total cumulative installed capacity of LE in China in the IEA-Current, IEA-New, IEA-Sustainable, NDRC-High RE scenarios will reach 1464, 1969, 2384 and 4848 GW respectively, accounting for 48%, 60%, 73% and 81% of the total respectively. The difference in scenarios provided by IEA and NDRC is associated with the growth of wind and solar power. The IEA-Current, IEA-New and IEA-Sustainable scenarios project an expansion of wind power at a growth rate far below that during 2002-2015, such that wind power in the IEA scenarios reach only 422, 593 and 814 GW by 2040 respectively. Only the NDRC-High RE scenario predicts for wind an average annual growth of 16% through 2040, such that wind power will reach 2092 GW by 2040. The three IEA scenarios predict 72-80% annual growth during 2015-2020, but their initial high growths are expected to slow dramatically to 4-6% for the period 2025-2040. The IEA-Current, IEA-New and IEA-Sustainable scenarios project solar power of 430, 738 and 835 GW by 2040 respectively. However, under the NDRC-High RE scenario, solar power demonstrates spectacular growth after 2025, which will grow 13% annually during 2025-2040 and reach 2.2 TW by 2040. In the IEA-Sustainable and NDRC-High RE scenarios, China will achieve a peak in thermal power capacity by 2035.

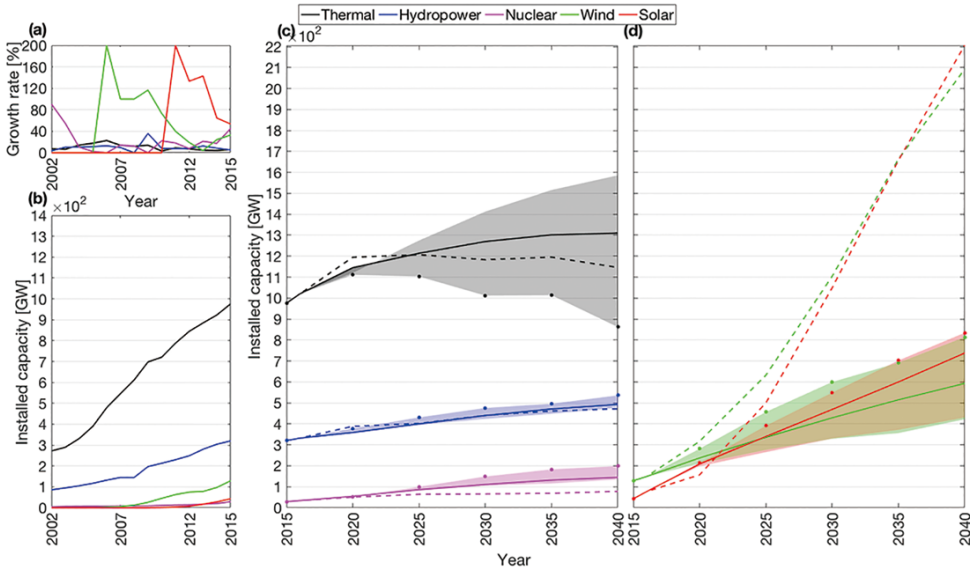


Fig.1. Growth in installed capacity of electricity technologies according to different scenarios: (a) annual growth rate of installed capacity; (b) historical cumulative installed capacity; (c) projections of thermal, hydro and nuclear power under four scenarios; (d) projections of wind and solar power under four scenarios. Note: solid lines show the projected cumulative installed capacity in the IEA-New scenario, while shades indicate a range of the projection of the IEA-Current scenario and IEA-Sustainable scenario. Solid dots show the projected cumulative installed capacity in the IEA-Sustainable scenario. Dashed lines show the projected cumulative installed capacity in the NDRC-High RE scenario. In the legend, color denotes electricity technology.

1.3. Related studies of carbon impact of low-carbon electricity in China

The decarbonization of the Chinese electricity system has attracted substantial research interest. Studies mainly focus on two aspects: impacts of LE expansion on historical carbon emissions (Hong et al., 2013, Dong et al., 2017, Ito, 2017, Mu et al., 2018, Xie et al., 2017, Xie et al., 2018), and prediction of the impact of LE expansion on carbon emissions in the future (Qi et al., 2014, Song et al., 2015, Sun et al., 2016, Pan et al., 2017, Zhao et al., 2017, Furlan and Mortarino, 2018, Liu et al., 2018). Perhaps unsurprisingly, these studies generally conclude that the development of LE will reduce emissions, but several also point out that LE investments tend to require more materials, and might therefore lead to high levels of infrastructure-related emissions (Arvesen and Hertwich, 2012, Amponsah et al., 2014, Hertwich, 2013, Hertwich et al., 2015). Although such emissions related to the expansion of LE infrastructure may be very important in the Chinese energy transition, on this subject there are still few quantitative studies available. Given the importance and scale of this transition, we investigate how the carbon impacts of LE investments will influence China's low-carbon electricity development.

1.4. Purpose and contributions

Here we analyze the carbon impacts of LE investments as reflected by the aforementioned energy scenarios for China. We consider four major LE technologies: hydro, nuclear, wind and solar power. We estimate the carbon impact of LE investments on the basis of

historic carbon intensity of LE installation, that is the carbon impact of per unit installed capacity of LE (MtCO₂/GW). We assess this evolution over the period 2002-2012 using a Multi-Regional Input-Output (MRIO) models discerning the 30 provinces of China. MRIO models allow for the estimation of direct and indirect carbon impacts from LE investments at provincial level in China (Miller and Blair, 2009). By using multiple provincial-level estimates we can provide both a mean and variance of the carbon intensity of different energy types. As carbon intensities of LE installation are found to decrease significantly with increased cumulative installed capacities, we establish experience curves to emphasize the potential of declining carbon intensity of LE installation. Finally, using estimated experience curves, we project carbon impacts of LE investments based on the growth of LE capacity in the four scenarios from IEA and NDRC outlined above.

We provide an evaluation of feasible ranges of carbon impacts LE investments up to 2040 by extrapolating information from historical data. Although we do not draw attention to the effect of LE development on carbon emissions in the operational phase, the integration of carbon impact of LE investments into carbon emissions projections complements the conventional analysis of operational phase emissions. Our analysis also highlights several lessons for other countries attempting to decarbonize their electricity system. This paper proceeds in four parts: Section 2 describes methods and data. Section 3 presents the main results. Section 4 presents a comparison with LCA studies, and an evaluation of uncertainty of projections. Section 5 concludes and outlines relevant policy implications.

2. Methods and data

2.1. Estimation of historical carbon intensity of installation

We first estimate the carbon intensity of installation (MtCO₂/GW) using MRIO models. Following the method developed by Hedi (2017), electricity investments are mapped against the MRIO table's classifications, and carbon impacts of LE investments are estimated:

$$q = B \times L \times V \times S \quad (1)$$

MRIO model comprises of n_R regions, each of them with n_S economic sectors. q is the carbon emissions from the investment in a particular electricity technology (Mt); B is a row vector of CO₂ emission coefficients with length $n_R n_S$, showing carbon emissions (MtCO₂) per unit of economic output (million yuan) of each sector; $L = (I - A)^{-1}$ is a square Leontief inverse matrix with side of length $n_R n_S$, and in turn A is a matrix of technical coefficients (expressing which inputs from other sectors are required to generate a unit of output of a given sector); V is a diagonal matrix with side of length $n_R n_S$, showing the investment scale of given electricity technology in a region (million yuan); S is an input share vector of length $n_R n_S$, which represents the investment cost structure of a given electricity technology.

Note that the analysis is performed separately for each technology in each region. If a region invested in an electricity technology, the main diagonal elements of V represent the investment scale of given electricity technology in this region, while elements of other regions on the main diagonal of V are all zeros. Moreover, the investment cost structure of each electricity technology is assumed to be identical for different periods and regions.

The carbon intensity of installation for an electricity technology can then be obtained from the new installed capacity of given electricity technology:

$$p_r = q_r / n_r \quad (2)$$

where r is an index referring to one of the 30 provinces, p is the emissions per unit of installed capacity (MtCO₂/GW); and n is the amount of new installed capacity (GW).

2.2. Projection of carbon intensity of installation

In order to evaluate the general performance of carbon intensities of installation for an electricity technology, we calculate the median and 95% confidence intervals of the carbon intensity of installation, p_r , using the 30 provinces as a sample, weighted by provincial installed capacity. Then, we extrapolate these experience curves to provide estimates of future carbon intensities. The relation between carbon intensity of installation and cumulative installed capacity is described referring to the experience curve (Samadi, 2018):

$$p_m = p_1 \times C^{-a} \quad (3)$$

where p_m is the carbon intensity of installation for the m units of an electricity technology, p_1 is the carbon intensity of installation for the first unit of a given electricity technology; C is the total cumulative installed capacity of a given electricity technology in China; $-a = \log_2(1 - l)$ is experience index of a given electricity technology, showing the decrease in carbon intensity of installation as a function of increased cumulative installed capacity; and l is the experience rate of a given electricity technology.

Since Eq.(3) is in an exponential form, the experience elasticity a can be converted to a linear function in a log scale (Zou, 2016):

$$\log(p_m) = \log(p_1) + a \times \log(C) \quad (4)$$

After estimating the slope of the linear function a , we can extrapolate the carbon intensity of LE installation for future cumulative installed capacities as suggested from the four IEA and NDRC scenarios (see Figure 1). Since our approach for calculating the carbon intensity of LE is using an MRIO model, in principle carbon reductions in the supply chain of the LE infrastructure (e.g. electricity sector itself) could also play a role in developing experience curves. We will discuss more details in section 4.2 to clarify the limited relevance of this effect.

2.3. Scenario analysis for carbon impacts of LE investments

Since the IEA and NDRC report the total cumulative installed capacity in China for five-year blocks until 2040, we obtain new installed capacity of LE in these five-year periods rather than each individual year. Thus, we project a range for the carbon impact of LE investments for each period by assuming that the carbon intensity is at the starting or last year of the projection. Mathematically, the upper (q^{upper}) and lower (q^{lower}) bound of carbon impacts of LE investments for a period is calculated as:

$$q^{upper} = n \times p^{start} \quad (5(1))$$

$$q^{lower} = n \times p^{last} \quad (5(2))$$

where n is the projected new installed capacity of a LE technology for given period, and p^{start} and p^{last} is the projected carbon intensity of installation of a given electricity technology in the starting and last year of given period respectively.

2.4. Data

The MRIO tables of China's 30 provinces for 2002, 2007, 2010, 2012 are obtained from Shi and Zhang (2012), Liu et al., (2012), Liu et al., (2014) and Mi et al., (2017), respectively. The 30 sectors listed in 2007, 2010 and 2012 tables and the 21 sectors listed in the 2002 table are aggregated to 21 sectors to obtain consistent tables for 2002, 2007, 2010 and 2012 (as shown in Table A1 in Appendix). We use official data, including the history of cement production and the consumption of energy and electricity, to estimate sectoral CO₂ emissions. We consider carbon emissions from cement production because cement is emissions-intensive, and is a major input in the construction of some energy types including hydropower and nuclear (less so for wind, and very minor for solar). We adopt the IPCC (2006) sectoral approach to calculate CO₂ emissions. CO₂ emissions equal activity data (fossil fuel consumption and cement production) multiplied with carbon emission factors. The activity data of fossil fuels for 2002, 2007, 2010 and 2012 are collected from the Provincial Energy Balance Tables reported by *China Energy Statistics Yearbook* (NBS, 2003a, 2008a, 2011a, 2013a). Since the Provincial Energy Balance Tables of China only supply regional fossil fuel consumptions at an aggregated sectoral level, the data of sub-sectoral fossil fuels consumption are from the Provincial Statistical Yearbooks of China's 30 provinces (NBS, 2003c, 2008c, 2011c, 2013c). The data of the annual cement production are collected from the *China Statistical Year book* (NBS, 2003b, 2008b, 2011b, 2013b). Carbon emission factors for fossil fuels (tonne CO₂/ tonnes, m³) and cement production (tonne CO₂/ tonnes) are collected from report of the IPCC (2006) and NDRC (2011). Electricity investment data comes from the *China Electric Power Yearbook* (CEPYEB, 2003, 2008, 2011) and *Annual development report of China's power sector* (CEC, 2003, 2008, 2011). The investment structure of LE refers to Dai et al., (2016), and the data for thermal power is collected from *Cost and Performance Baseline for Fossil Energy Plants* (NETL, 2010). The projected data of cumulative installed capacity are collected from *World Energy Outlook* (IEA, 2017, 2016, 2013) and *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* (NDRC, 2015). The detailed installed capacity schedule for each five-year from 2015 to 2040 is reported by the NDRC, while the IEA estimates for 2020 and 2035 are absent in the 2017 report. Since estimates for such years exist in the IEA reports of 2013 and 2016, we use linear interpolation to adjust the projection of IEA 2013 and 2016 so that successive reports between 2015 and 2040 can be obtained.

3. Results

3.1. Historical carbon intensity of LE installation

Figure 2 shows the median value and variability of 30 provincial-level estimates of carbon intensity of installation depending on the China's total cumulative installed capacity in 2002, 2007, 2010 and 2012. Figure A1 contains the corresponding results for the carbon intensity of LE installation in 30 provinces during 2002-2012. The result shows little variation in the median of carbon intensity of thermal power installation with increased cumulative installed capacity, being stable at 0.48-0.50 MtCO₂/GW. However, there is a clear downward trend for carbon intensity of LE installation. For example, the median of hydropower installation carbon intensity decreased from 2.12 to 0.71 MtCO₂/GW during 2002-2012, when cumulative installed capacity of hydropower increased from 83 GW in 2002 to 249 GW in 2012. Using experience curve models, Figure 2 also plots the relationship between the median for carbon intensity of installation and China's total

cumulative installed capacity. Table A2 shows that correlation coefficients, indicating the robustness of the estimated experience curve, are high for all LE technologies ($R^2 > 95\%$). Using the derived experience curves, we project future carbon intensities of LE installation during 2015-2040 based on increased cumulative capacity in China under the four scenarios from IEA and NDRC, see Table A3.

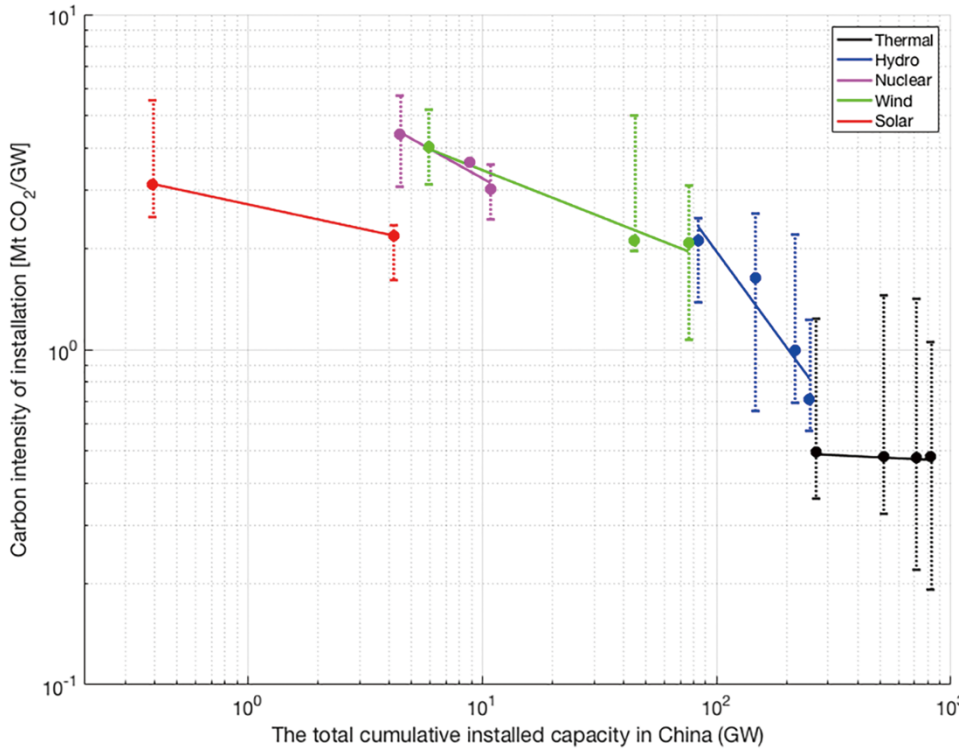


Fig.2. Experience curves for LE technologies. Solid lines reflect resulting experience curves for different electricity technologies based on linear regression of the data. Dots represent median estimates. Error bars represent 95% confidence interval estimates. In the legend, color denotes electricity technology.

3.2. Outlook for carbon impacts of LE investments

Figure 3(b) shows the projected carbon impacts of LE investments up to 2040. For the in-depth assessment of carbon implication of future LE investments (details are shown in Table A4), we also compare projected carbon impact of LE investments with the projection of China's total carbon emissions up to 2040, as reported by the IEA and NDRC (see Figure 3(a)). In the IEA-Current and IEA-New scenarios, the cumulative carbon impact of LE investments during 2015-2020 is 377 Mt and 423 Mt respectively. Since Figure 3(a) shows China's total carbon emissions in a particular year, a more useful measurement is the annualized carbon impact of LE investments. Under the IEA-Current and IEA-New scenarios, the average annual carbon impact of LE investments during 2015-2020 is 75 Mt and 85 Mt respectively. Thus, the share of average annual carbon impact of LE investments for the period of 2015-2020 relative to China's total carbon emissions in 2020 under the IEA-Current and IEA-New scenarios is 0.81% and 0.93%

respectively. The cumulative carbon impact of LE investments for the period of 2035-2040 in IEA-Current and IEA-New scenarios decreases to 180 Mt and 250 Mt respectively. Similar to the above measurement, the average annual carbon impact of LE investments during 2035-2040 under the IEA-Current and IEA-New scenarios is 40 Mt and 50 Mt respectively, which account for 0.32% and 0.58% of China's total carbon emissions in 2040 respectively. In comparison with IEA-Current and IEA-New scenarios, the annual average carbon impact of LE investments in IEA-Sustainable and NDRC-High RE scenarios are a larger component of China's total carbon emissions. In the IEA-Sustainable and NDRC-High RE scenarios, the annual carbon impact of LE investments for the period 2015-2020 is 98 Mt and 94 Mt respectively, accounting for 1.13% and 1.02% of China's total carbon emissions in 2020 respectively. By 2040, the annual carbon impact of LE investments for the period 2035-2040 relative to China's total carbon emissions under the IEA-Current and IEA-New scenarios increases to 1.74% and 3.10% respectively. Generally, in all scenarios and every year, the annual carbon impact of LE investments never exceeds 4% of China's total carbon emissions.

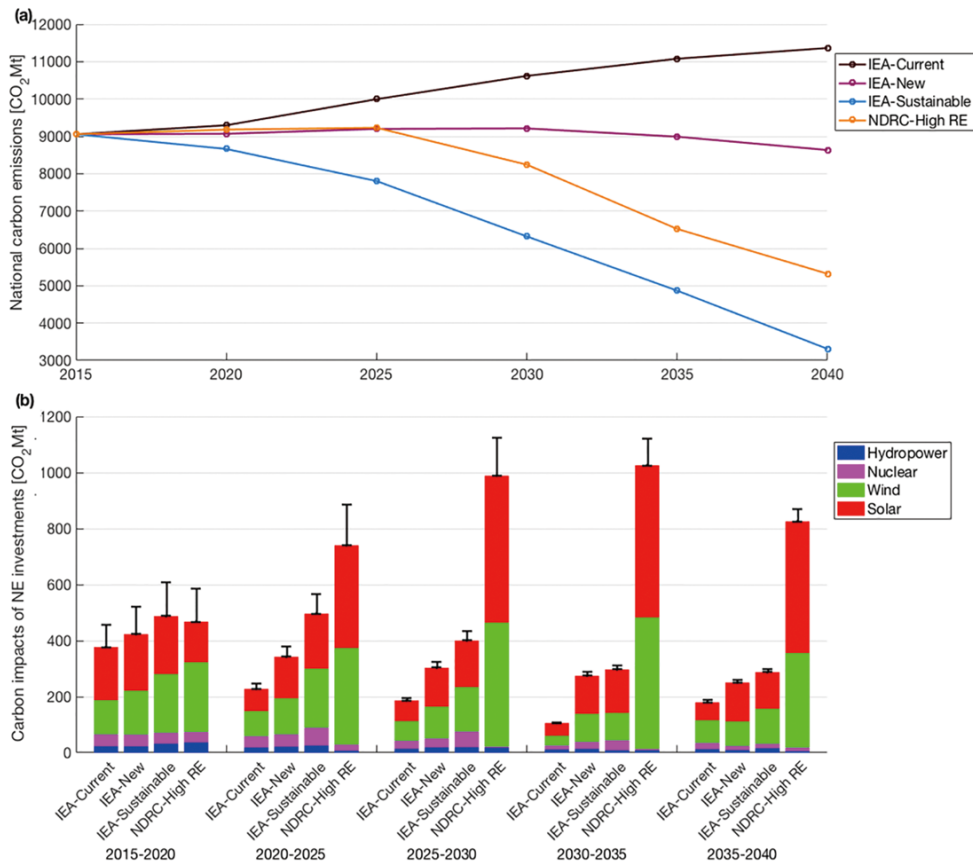


Fig.3. Carbon impacts of LE investments during 2015-2040: (a) total carbon emissions in China during 2015-2040 from IEA and NDRC scenarios; (b) estimated cumulative carbon impacts of LE investments for each 5-year period of 2015-2040. That is, each tick across the x-axis shows a 5-year period, with each of the stacked bars, and the y-axis showing the total emissions over that 5-year

period. Note: stacked bar charts indicate projected carbon impacts of LE investments based on carbon intensity of LE installation in the last year during each period, which is the lower bound of results. Error bars show the difference between upper and lower bound in the carbon impact of LE investments as described in the Methods.

3.3. Differences among projections under four scenarios

Figure 3 also shows the differences among projections under four scenarios. In the IEA-Current scenario, China's total carbon emissions will rise gradually, stabilizing at 11364 Mt by 2040, while China's total carbon emissions in the IEA-New scenario peaks at 9212 Mt in 2030 and then declines to 8633 in 2040. In the IEA-Sustainable and NDRC-High RE scenarios, China's total carbon emissions reduce by 63% and 41% from 2015 to 2040 respectively. China's total carbon emissions in the NDRC-High RE scenario is higher than IEA-Sustainable scenario although wind and solar power will increase fast in the NDRC-High RE scenario. This is because the cumulative capacity of thermal power in the NDRC-High RE scenario is significantly larger than in the IEA-Sustainable scenario (see Figure 1). The carbon impact of LE investments in the NDRC-High RE scenario is larger than that of other scenarios. The carbon impact of LE investments in the IEA-Current, IEA-Policy and IEA-Sustainable scenarios show a downward trend, falling by 59%, 50% and 51% between the 2015-2020 period and the 2035-2040 period. In the NDRC-High RE scenario, from 2015-2035, the carbon impact of LE investments shows a sharp growth, while the carbon impact of LE investments reaches a peak during 2030-2035 (1021 Mt), after which it gradually declines to 826 Mt during 2035-2040. Overall, for all scenarios, during 2035-2040, the continuous increase in LE is expected to bring the most significant declines in carbon emissions while the carbon impact of LE investments drops.

4. Discussion

4.1. Comparison with results from LCA studies

The carbon impact of LE investments also can be estimated using Life Cycle Assessment (LCA). LCA can address emissions associated from the construction plant and the dismantling of a plant (Suh and Huppes, 2005, Crawford et al., 2018). To assess the carbon impact of LE investments, several researchers have performed systematic reviews and harmonization of LCA studies by establishing a compatible set of system parameters and a standard methodology (Hsu, et al., 2012, Hyung et al., 2012, Menten et al., 2013, Hertwich et al., 2015, Atse et al., 2016). These studies provide estimates of average life-cycle emissions (Asdrubali et al., 2015), the distribution of life-cycle emissions over life-cycle stages (Turconi et al., 2013), and the factors influencing results of LCAs (Raadal et al., 2011, Warner and Heath, 2012). However, there are challenges in clarifying the carbon impact of LE investments in China using such harmonized data. Since the accuracy of LCA is dependent on geographical factors (Ding et al., 2017), assessments generally require China-specific values. However, most LCA studies in China focus only on recent years (solar: Fu et al., 2015, Yang et al., 2015, Xu et al., 2018, wind: Xue et al., 2015, Xu et al., 2017, nuclear: Ou et al., 2011, Jiang et al., 2015, and hydro: Hu et al., 2013, Pang et al., 2015, Li et al., 2017), and with limited number of China's LCAs available for low-carbon electricity in each year. Thus, a review of China's LCA studies covering a short period cannot reflect the dynamic of carbon intensity of installation well. Moreover, most LCA studies for China only assess carbon emissions per unit of LE

generation (gCO_2/kWh), while the infrastructure-related emissions are rarely separately reported in LCAs.

Comparing our estimates of carbon intensity of LE installation with LCA studies can give further insights, as infrastructure is the major contributing sub-stage to LE's life-cycle emissions (Lenzen and Munksgaard, 2002, Warner and Heath, 2012, Turconi et al., 2013). Since we analyze carbon emissions induced by electricity investments (MtCO_2/GW) and LCAs often report the carbon emissions per kWh of generated electricity (gCO_2/kWh), we converted the carbon intensity of installation to the appropriate unit (see the methods in Appendix). Figure 4 shows a comparison with life-cycle emissions of LE from published LCA studies (data see Table A5-A9). Since LCA case studies included in the Figure 4 is not only based on a review of China's LCA studies, the life-cycle emissions of LE presented here are from multi-countries/regions. In order to explore a correlation between life-cycle emissions of LE and time, Figure 4 captures the variation of carbon intensity (gCO_2/kWh) from a perspective of global cumulative installed capacity in the period 2002-2012. The decreased trend of LE's life-cycle emissions in Figure 4 is in line with our results, confirming that carbon impacts of LE investments have a good correlation with cumulative installed capacity. Moreover, our estimates for thermal, hydro, nuclear and wind power are close to results of LCA studies. However, our estimates for solar power are higher than results of LCA studies. This may be because the manufacturing process of solar systems in China could result in more emissions than the same processes in other countries, as China's electricity generation is highly dependent on coal (Peng et al., 2013, Nugent and Sovacool, 2014). Generally, our estimates are within the range of results from LCA studies.

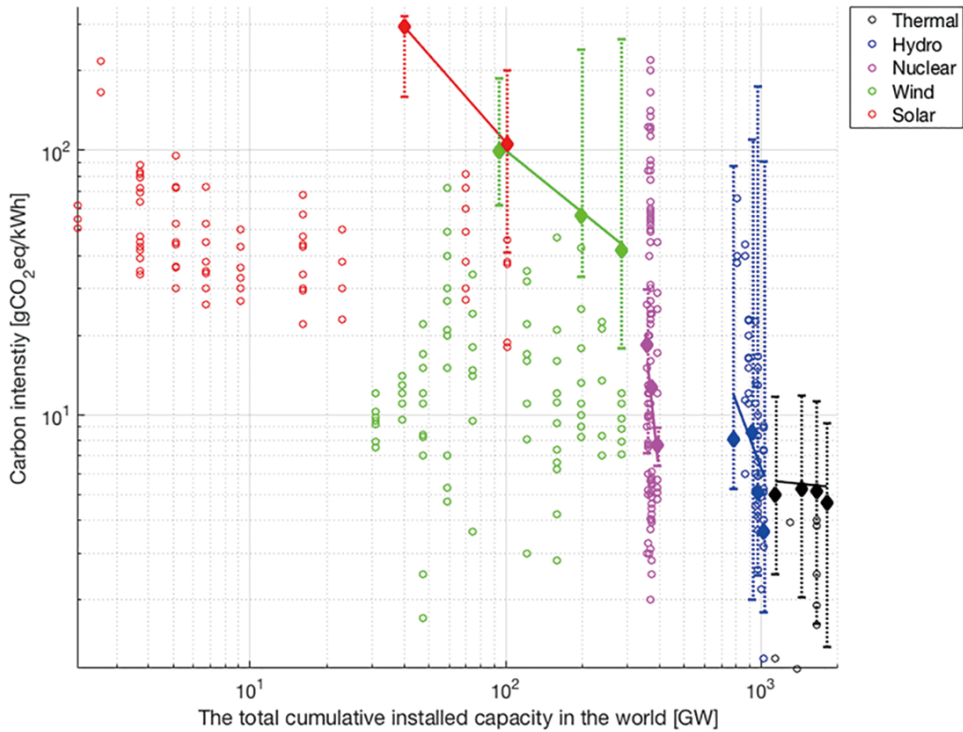


Fig.4. Summary of life-cycle emissions from different electricity technologies based on global cumulative installed capacity over the period 2002-2012. Note: solid dots represent individual estimates from the literature. Since power generation is the major contributing sub-stage to carbon emissions for thermal power, reported total life-cycle emissions of thermal power are replaced with carbon emissions in the infrastructure phase. Error bars indicate the range of our estimated 30 provinces' carbon intensity of installation. Diamonds reflect the median of carbon intensity of installation. Color in legend indicates the electricity technology.

4.2. Evaluating the uncertainties of the projection

The experience curve (or learning curve) describes the way that performance, such as lowering material inputs, costs, and emissions, develops as industries gain more experience through producing products. Since it is based on the amount of product made, performance increases are taken from the perspective of cumulative capacity and the carbon intensity of LE installation. Due to the empirical, rather than analytical, nature of experience curves, cumulative capacity is only one of several explanations for reductions of carbon intensity of installation. Therefore, extrapolations are subject to the uncertainties underlying the derived experience rates (Fukui et al., 2017). Our analysis does not allow for the feedbacks whereby increasing LE investments result in an electricity system with lower carbon emissions. Any declines in the carbon intensity of LE investments would decrease the carbon intensity of electricity generation which would create a feedback for further emission reductions. Thus, the involvement of carbon performance of electricity sector into learning loops requires the incorporation of the carbon intensity of electricity generation (gCO_2/kWh). In order to better put our experience curve into perspective, we discuss the effect of electricity system itself on LE

investments in the future. We find that given the reduced carbon intensity of electricity generation, during 2002-2012 (see Figure 5(a)), the contribution of electricity sector to carbon impact of LE investments gradually declined (see Figure 5(b)-(e)). This means that the experience curves could have a role to play in decarbonizing electricity sector due to learning investments bringing down the environmental costs of LE installation. Thus, the reduction of carbon intensity of LE installation with increased cumulative capacity could be amplified by the improvement of carbon performance of electricity sector. We can hypothesize that the actual carbon impacts of LE investments from 2015 to 2040 could be lower than estimated results. However, from Figure 5 (a), we also can find that the decline has flattened, and the carbon intensity of generation in 2012 is almost similar to the value of 2010. This may indicate that there is minimal room left for additional loop effect of electricity system on LE investments as not much more experience can be acquired in the relatively stable electricity system. Thus, although the emission reduction of electricity system influences the extrapolation of the experience curve, it will offer small opportunity for continued decline in carbon intensity of LE installation. Therefore, the change of electricity system is not explicitly taken into account in experience curve analysis.

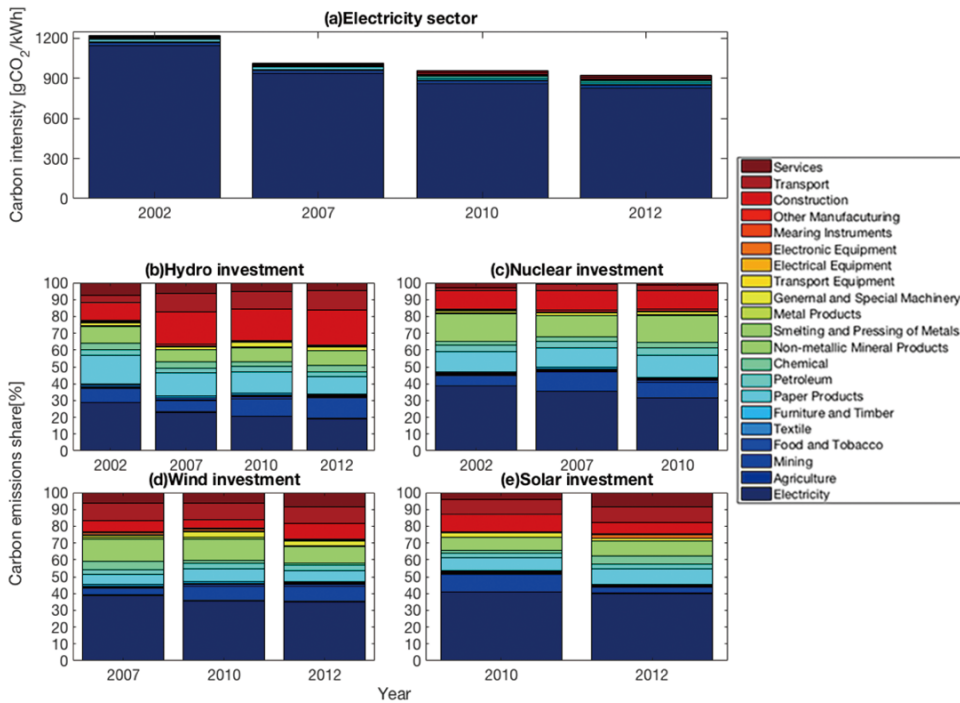


Fig.5. The evolution of carbon impact of electricity sector: (a) the evolution of carbon intensity of electricity generation (gCO₂/kWh); (b)-(e) the contribution of electricity sector to the total carbon impact of LE investments (%).

5. Conclusions and policy implications

Although LE provides more carbon savings in the operational phase than fossil-fuel electricity, LE infrastructure tends to require more materials than their fossil-fuel electricity counterpart. In order to estimate carbon overhead from infrastructure expansion, we project the carbon impact of LE investments up to 2040. We find that in the IEA-Sustainable and NDRC-High RE scenarios, the development of LE will lead to larger emission reductions, but the carbon impact of LE investments will also account for a larger share of China's total carbon emissions. In the IEA-Sustainable and NDRC-High RE scenarios, the average annual carbon impact of LE investments relative to China's total carbon emissions will increase to 1.74% and 3.10% during 2035-2040 from 1.13% and 1.02% during 2015-2020 respectively. The carbon impacts of LE investments in all IEA scenarios show a steady decline trend. The NDRC-High RE scenario shows a larger carbon impact of LE investment than IEA scenarios with the rapid development of wind and solar power. However, the carbon impact of LE investments in the NDRC-High RE scenario will reach a peak during 2030-2035. The carbon impact of LE investments in all scenarios will have consistent performance during 2035-2040, reaching their lowest level in that period.

Based on the above conclusions, policy makers can have more information to make a comprehensive action plan for LE development. During 2035-2040, according to all scenarios we will see large reductions in carbon impact of LE investment. Evidently, scaling up deployment of LE will eventually contribute towards a more sustainable electricity sector. Moreover, the carbon impact of LE investments will take up a small percentage of China's total carbon emissions in all scenarios (less than 4%). This indicates that the carbon overhead from LE infrastructure expansion is small, in a relative sense, compared to total CO₂ emissions. Thus, the carbon impact of LE investments cannot be used as an argument to suggest halting LE expansion. In the future, there is a large potential for increasing the contribution of LE development to future emissions reductions in China, if climate policies can be implemented based on LE development goals under the IEA-Sustainable scenario.

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Appendix

Conversion unit for carbon intensity of installation

We converted carbon intensity of installation (MtCO_2/GW) to the appropriate unit (gCO_2/kWh), so that our estimates can be compared with results from LCA studies:

$$p = \frac{q}{F \times n \times T \times \left(1 - d \times \frac{T}{2}\right)} \quad (\text{A.1})$$

where p is the carbon intensity of installation with the unit of gCO_2/kWh ; F is the equivalent annual full load hours; n is the annual new installed capacity; T is the lifetime of electricity investment project (30 years for thermal, wind and solar power, 100 years for hydropower, 60 years for nuclear power); d is a degradation rate (0.15% for thermal and nuclear power (MacDonald, 2010, Arup, 2011), 0.3% for hydropower (IRENA, 2012), 0.4% for wind (Staffell and Green 2014), 0.7% for solar (Atse et al., 2016)).

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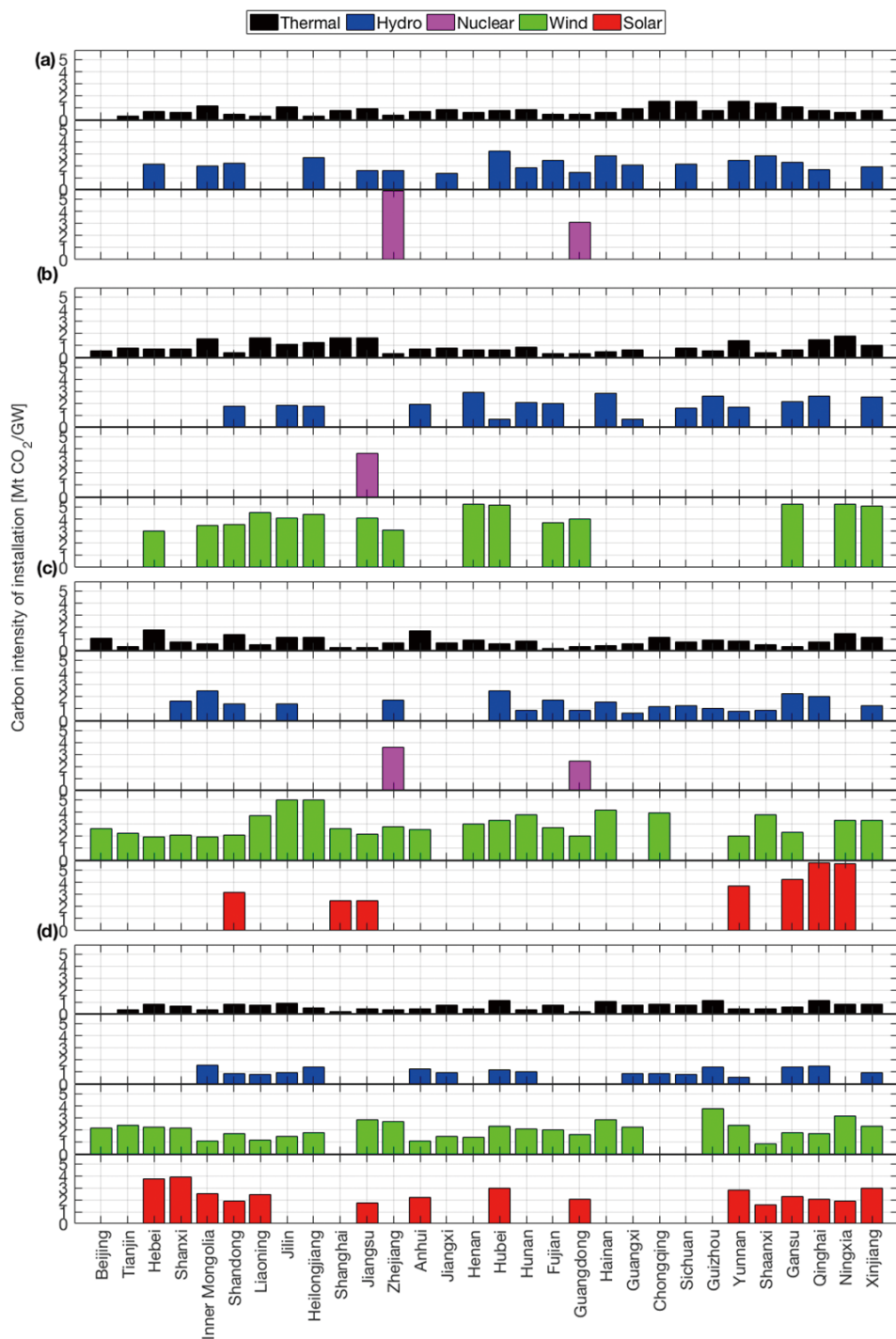


Fig.A1. The estimated carbon intensity of installation for five electricity technologies in 30

provinces during 2002-2010:(a) 2002; (b) 2007; (c) 2010; (d) 2012.

Table A1. Sector classifications for the Chinese economy.

Code	Sector
1	Agriculture
2	Mining
3	Food and Tobacco
4	Textile
5	Processing of Timber and Furniture
6	Paper and Paper Products
7	Petroleum Refining and Coking
8	Chemical
9	Non-metallic Mineral Products
10	Smelting and Pressing of Metals
11	Metal Products
12	General Equipment
13	Transport Equipment
14	Electric Machinery and Equipment
15	Electronic Equipment
16	Mearing Instruments and Machinery of Cultural Activity and Office Work
17	Other Manufacturing
18	Electricity
19	Construction
20	Transportation
21	Services

Table A2. The estimated learning curves for LE.

$\log(p_m)=a*\log(C)+\log(p_1)$	a	$\log(p_1)$	R^2
Thermal	-0.0344	2.8747	0.9510
Hydro	-0.9552	8.0683	0.9540
Nuclear	-0.3903	5.0727	0.9551
Wind	-0.2760	4.6399	0.9855
Solar	-0.1498	3.8829	1.0000

Table A3. The projected carbon intensity of installation under different scenarios (MtCO₂/GW).

Scenarios	Thermal	Hydro	Nuclear	Wind	Solar
IEA-Current					
2015	0.47	0.65	2.14	1.70	1.54
2020	0.46	0.58	1.68	1.48	1.23
2025	0.46	0.53	1.42	1.37	1.18
2030	0.46	0.49	1.30	1.31	1.14
2035	0.46	0.47	1.25	1.28	1.12
2040	0.46	0.44	1.18	1.22	1.09
IEA-New					
2015	0.47	0.65	2.14	1.70	1.54
2020	0.46	0.58	1.68	1.43	1.22
2025	0.46	0.52	1.40	1.30	1.13
2030	0.46	0.48	1.27	1.22	1.08
2035	0.46	0.45	1.19	1.16	1.04
2040	0.46	0.43	1.14	1.11	1.01
IEA-Sustainable					
2015	0.47	0.65	2.14	1.70	1.54

2020	0.46	0.55	1.71	1.37	1.21
2025	0.46	0.49	1.32	1.20	1.11
2030	0.47	0.44	1.13	1.11	1.05
2035	0.47	0.42	1.04	1.07	1.02
2040	0.47	0.39	1.01	1.02	0.99
NDRC-High RE					
2015	0.47	0.65	2.14	1.70	1.54
2020	0.46	0.54	1.73	1.32	1.27
2025	0.46	0.52	1.57	1.09	1.07
2030	0.46	0.48	1.55	0.94	0.96
2035	0.46	0.46	1.53	0.84	0.89
2040	0.46	0.45	1.46	0.79	0.86

Table A4. Projection of carbon impacts of NE investments.

Periods	Scenarios	LE technologies	New installed capacity (GW)	Carbon intensity of LE installation (MtCO ₂ /GW)		Carbon impacts of LE investments (MtCO ₂)	
				High	Low	High	Low
2015-2020	IEA-Current	Hydro	40	0.65	0.58	25.8	23.0
		Nuclear	25	2.14	1.68	54.6	42.7
		Wind	82	1.70	1.48	138.9	121.3
		Solar	155	1.54	1.23	238.8	190.0
	IEA-New	Hydro	39	0.65	0.58	25.0	22.4
		Nuclear	25	2.14	1.68	54.4	42.5
		Wind	109	1.70	1.43	184.5	155.8
		Solar	166	1.54	1.22	256.0	202.1
	IEA-Sustainable	Hydro	59	0.65	0.55	37.8	32.2
		Nuclear	23	2.14	1.71	49.0	39.1
		Wind	152	1.70	1.37	258.5	208.4
		Solar	171	1.54	1.21	264.3	207.8
	NDRC-High RE	Hydro	68	0.65	0.54	44.1	36.7
		Nuclear	22	2.14	1.73	46.1	37.1
		Wind	188	1.70	1.32	319.0	248.8
		Solar	114	1.54	1.27	176.1	145.1
2020-2025	IEA-Current	Hydro	35	0.58	0.53	20.2	18.5
		Nuclear	29	1.68	1.42	47.8	40.5
		Wind	65	1.48	1.37	96.4	89.5
		Solar	67	1.23	1.18	82.8	79.3
	IEA-New	Hydro	41	0.58	0.52	23.9	21.5
		Nuclear	32	1.68	1.40	53.0	44.4
		Wind	98	1.43	1.30	140.7	127.9
		Solar	131	1.22	1.13	160.0	148.7
	IEA-Sustainable	Hydro	52	0.55	0.49	28.8	25.5
		Nuclear	48	1.71	1.32	82.2	63.6
		Wind	176	1.37	1.20	240.1	210.0
		Solar	178	1.21	1.11	216.0	197.3
	NDRC-High RE	Hydro	14	0.54	0.52	7.5	7.2
		Nuclear	14	1.73	1.57	23.3	21.2
		Wind	315	1.32	1.09	416.9	344.6
		Solar	343	1.27	1.07	436.6	367.0
2025-	IEA-Current	Hydro	29	0.53	0.49	15.3	14.3

2030	IEA-New	Nuclear	22	1.42	1.30	31.3	28.5
		Wind	53	1.37	1.31	72.9	69.4
		Solar	65	1.18	1.14	76.5	74.0
		Hydro	40	0.52	0.48	20.9	19.0
	IEA-Sustainable	Nuclear	25	1.40	1.27	35.1	31.7
		Wind	93	1.30	1.22	121.1	113.2
		Solar	129	1.13	1.08	146.2	139.3
		Hydro	45	0.49	0.44	21.9	19.9
	NDRC-High RE	Nuclear	49	1.32	1.13	64.8	55.4
		Wind	143	1.20	1.11	171.0	158.7
		Solar	158	1.11	1.05	175.3	166.6
		Hydro	38	0.52	0.48	19.9	18.2
	IEA-Current	Nuclear	2	1.57	1.55	3.1	3.1
		Wind	472	1.09	0.94	515.9	442.4
		Solar	549	1.07	0.96	586.7	525.1
		Hydro	24	0.49	0.47	12.0	11.4

2030-2035	IEA-New	Nuclear	11	1.30	1.25	14.4	13.9
		Wind	27	1.31	1.28	35.4	34.6
		Solar	41	1.14	1.12	46.9	46.1
		Hydro	31	0.48	0.45	14.8	13.8
	IEA-Sustainable	Nuclear	21	1.27	1.19	26.7	24.9
		Wind	86	1.22	1.16	104.7	99.5
		Solar	131	1.08	1.04	141.5	136.3
		Hydro	20	0.44	0.42	9.0	8.6
	NDRC-High RE	Nuclear	34	1.13	1.04	38.4	35.5
		Wind	92	1.11	1.07	101.9	98.0
		Solar	153	1.05	1.02	161.1	155.3
		Hydro	20	0.48	0.46	9.5	9.1
	IEA-Current	Nuclear	3	1.55	1.53	4.7	4.6
		Wind	559	0.94	0.84	524.5	468.4
		Solar	608	0.96	0.89	582.2	543.6
		Hydro	29	0.47	0.44	13.4	12.6
	IEA-New	Nuclear	19	1.25	1.18	23.5	22.2
		Wind	66	1.28	1.22	84.6	80.7
		Solar	59	1.12	1.09	65.8	64.3
		Hydro	22	0.45	0.43	9.8	9.4
	IEA-Sustainable	Nuclear	13	1.19	1.14	15.4	14.9
		Wind	78	1.16	1.11	90.3	86.8
		Solar	138	1.04	1.01	143.6	139.2
		Hydro	40	0.42	0.39	16.9	15.7
	NDRC-High RE	Nuclear	16	1.04	1.01	16.7	16.2
		Wind	122	1.07	1.02	130.3	124.6
		Solar	132	1.02	0.99	134.4	131.0
		Hydro	11	0.46	0.45	5.0	4.9
	IEA-Current	Nuclear	9	1.53	1.46	13.8	13.1
		Wind	429	0.84	0.79	359.1	337.1
		Solar	549	0.89	0.86	490.9	470.3
		Hydro	29	0.47	0.44	13.4	12.6

2035-2040	IEA-New	Nuclear	19	1.25	1.18	23.5	22.2
		Wind	66	1.28	1.22	84.6	80.7
		Solar	59	1.12	1.09	65.8	64.3
		Hydro	22	0.45	0.43	9.8	9.4
	IEA-Sustainable	Nuclear	13	1.19	1.14	15.4	14.9
		Wind	78	1.16	1.11	90.3	86.8
		Solar	138	1.04	1.01	143.6	139.2
		Hydro	40	0.42	0.39	16.9	15.7
	NDRC-High RE	Nuclear	16	1.04	1.01	16.7	16.2
		Wind	122	1.07	1.02	130.3	124.6
		Solar	132	1.02	0.99	134.4	131.0
		Hydro	11	0.46	0.45	5.0	4.9
	IEA-Current	Nuclear	9	1.53	1.46	13.8	13.1
		Wind	429	0.84	0.79	359.1	337.1
		Solar	549	0.89	0.86	490.9	470.3
		Hydro	29	0.47	0.44	13.4	12.6
	IEA-New	Nuclear	19	1.25	1.18	23.5	22.2
		Wind	66	1.28	1.22	84.6	80.7
		Solar	59	1.12	1.09	65.8	64.3
		Hydro	22	0.45	0.43	9.8	9.4
	IEA-Sustainable	Nuclear	13	1.19	1.14	15.4	14.9
		Wind	78	1.16	1.11	90.3	86.8
		Solar	138	1.04	1.01	143.6	139.2
		Hydro	40	0.42	0.39	16.9	15.7
	NDRC-High RE	Nuclear	16	1.04	1.01	16.7	16.2
		Wind	122	1.07	1.02	130.3	124.6
		Solar	132	1.02	0.99	134.4	131.0
		Hydro	11	0.46	0.45	5.0	4.9
	IEA-Current	Nuclear	9	1.53	1.46	13.8	13.1
		Wind	429	0.84	0.79	359.1	337.1
		Solar	549	0.89	0.86	490.9	470.3
		Hydro	29	0.47	0.44	13.4	12.6

Table A5. Data for infrastructure-related carbon emissions for thermal power.

Reference	Data Year	Location	Life (Years)	Reported (gCO ₂ eq/kWh)
Meier et al., 2005	2002	USA	30	1.2
Hondo, 2005	2005	Japan	30	3.9

Odell et al., 2008	2006	UK	40	1.1
NETL, 2010b	2010	USA	30	1.6
NETL, 2010b	2010	USA	30	2.5
NETL, 2010b	2010	USA	30	4.0
NETL, 2010a	2010	USA	30	1.9
Steinmann et al., 2014	2010	USA	20	3.8

Note: we use the base year mentioned in literatures as data year. While some papers do not mention their base year, we use published year as data year. Life (years) is estimated years of service time.

Table A6. Data for life-cycle carbon emissions for hydropower.

Reference	Data Year	Location	Life (Years)	Reported (gCO ₂ eq/kWh)
Denholm et al., 2004	2003	USA, Germany	60	37.5
Horvath, 2005	2003	USA: Arizona	20	66
Horvath, 2005	2003	USA: Arizona	20	40
Hondo, 2005	2005	Japan	30	11.3
Pacca, 2007	2005	USA: Arizona	100	40
Zhang et al., 2007	2005	China	100	6
Zhang et al., 2007	2005	China	100	44
Santoyo-Castelazo et al., 2011	2006	Mexico	100	12
Lenzen, 2008	2006	Australia	100	15
Pascale et al., 2011	2006	Thailand	20	20
Suwanit et al., 2011	2006	Thailand	50	22.7
Suwanit et al., 2011	2006	Thailand	50	16.3
Suwanit et al., 2011	2006	Thailand	50	16.5
Suwanit et al., 2011	2006	Thailand	50	23
Suwanit et al., 2011	2006	Thailand	50	11
Amor et al., 2011.	2008	USA	100	11
Axpo, 2011	2008	Swiss	80	5.2
Axpo Nuclear Energy, 2008	2008	Swiss	60	4.5
Feng et al., 2014	2008	China		13.2
Mallia and Lewis, 2013.	2008	Canada	100	22.5
Vattenfall, 2008	2008	Sweden		6
Atilgan and Azapagic, 2016	2010	Turkey	150	8.3
Atilgan and Azapagic, 2016	2010	Turkey	150	4.1
Covenant of Mayors, 2010.	2010	Europe		10
Covenant of Mayors, 2010.	2010	Europe		13
Donnelly et al., 2010	2010	Worldwide	100	15
Donnelly et al., 2010	2010	Worldwide	100	5
Flury and Frischknecht, 2016	2010	Europe: alpine	150	5.9
Flury and Frischknecht, 2016	2010	Europe: non-alpine	150	16.7
García-Gusano et al., 2016	2010	Norway	50	6.7
García-Gusano et al., 2016	2010	Norway	50	3.7
Hidrovo et al., 2017	2010	Ecuador	80	2.6
Ribeiro and da Silva, 2010	2010	Brazilian	100	4.3
Rule et al., 2009	2010	New Zealand	100	4.6
Arnøy and Ingunn, 2013	2011	Norway	100	2.2
Raadal et al., 2011	2011	Worldwide		4.9
Valente, 2015	2011	Italy		6
Axpo, 2016.	2012	Swiss	100	3.2
Axpo, 2016.	2012	Swiss	100	5.2
Hanafi and Riman, 2015	2012	Indonesia	50	1.2
IPCC, 2012	2012	China		4
Kuo, 2014.	2012	USA		7.4

Li et al., 2017	2012	China	100	9.1
Li et al., 2017	2012	China	100	7.3
Li et al., 2017	2012	China	100	9.0
Zhang et al., 2015	2012	China		5.1

Table A7. Data for life-cycle carbon emissions for nuclear power.

Reference	Data Year	Location	Life (Years)	Reported (gCO ₂ eq/kWh)
Meier et al, 2005	2002	USA	30	18.4
van Vate, 2002.	2002	Swiss	40	8.9
Kulcinski, 2002	2002	USA		15
Dones et al, 2004	2002	Swiss and Europe	40	9
Delucchi, 2003	2002	USA		26
Ruether et al,2004	2002	USA	30	3
Dones et al, 2005	2003	Swiss and Europe	40	5
Dones et al, 2005	2003	Swiss and Europe	40	12
Dones et al, 2007	2003	Swiss and Europe	40	11
Dones et al, 2007	2003	Swiss and Europe	40	11
Dones et al, 2007	2003	Swiss and Europe	40	7.5
Dones et al, 2007	2003	Swiss and Europe	40	7.8
Dones et al, 2007	2003	Swiss and Europe	40	10
Dones et al, 2007	2003	Swiss and Europe	40	7.7
Dones et al, 2007	2003	Swiss and Europe	40	5.2
Dones et al, 2007	2003	Swiss and Europe	40	5.2
Dones et al, 2007	2003	Swiss and Europe	40	9.8
Dones et al, 2007	2003	Swiss and Europe	40	6
Dones et al, 2007	2003	Swiss and Europe	40	7.7
Dones et al, 2007	2003	Swiss and Europe	40	13
Fthenakis and Alsema, 2006	2003	Germany	40	20
van Leeuwen and Smith, 2005	2003	Netherlands	25	84
van Leeuwen and Smith, 2005	2003	Netherlands	25	122
Vattenfall, 2005.	2003	Sweden	40	3.3
WEC, 2004	2004	Australia		40
WEC, 2004	2004	Germany		20
WEC, 2004	2004	Sweden		3
WEC, 2004	2004	Sweden		3
WEC, 2004	2004	UK		12
British Energy, 2005	2005	UK	40	5.1
Echávarri, 2007	2005	OECD		4.1
Fritsche and Lim, 2006	2005	Germany		64
Hondo, 2005	2005	Japan	30	10
Hondo, 2005	2005	Japan	30	30
Hondo, 2005	2005	Japan	30	24
Hondo, 2005	2005	Japan	30	27
Hondo, 2005	2005	Japan	30	27
Hondo, 2005	2005	Japan	30	22
Hondo, 2005	2005	Japan	30	24
Hondo, 2005	2005	Japan	30	11
Hondo, 2005	2005	Japan	30	27
Hondo, 2005	2005	Japan	30	22
Hondo, 2005	2005	Japan	30	23
Hondo, 2005	2005	Japan	30	23
Fleming, 2007	2005	UK	60	88
Fleming, 2007	2005	UK	60	134

van Leeuwen, 2006	2005		100	92
van Leeuwen, 2006	2005		100	141
Vattenfall, 2007	2005	Sweden	50	3.7
Axpo Nuclear Energy, 2008	2006	Swiss	60	3.1
Barnaby and Kemp, 2007	2006	UK	35	84
Barnaby and Kemp, 2007	2006	UK	35	122
Fthenakis and Kim, 2007.	2006	Canada	40	16
Fthenakis and Kim, 2007.	2006	Canada	40	25
Fthenakis and Kim, 2007.	2006	Canada	40	55
Lenzen et al, 2006	2006	Australia	30	55
Lenzen et al, 2006	2006	Australia	30	58
Lenzen et al, 2006	2006	Australia	30	56
Lenzen et al, 2006	2006	Australia	25	54
Lenzen et al, 2006	2006	Australia	25	59
Lenzen et al, 2006	2006	Australia	45	58
Lenzen et al, 2006	2006	Australia	30	64
Lenzen et al, 2006	2006	Australia	30	49
Lenzen et al, 2006	2006	Australia	30	77
Lenzen et al, 2006	2006	Australia	30	45
Lenzen et al, 2006	2006	Australia	30	50
Lenzen et al, 2006	2006	Australia	30	60
Lenzen et al, 2006	2006	Australia	30	56
Lenzen et al, 2006	2006	Australia	30	55
Lenzen et al, 2006	2006	Australia	30	52
Lenzen et al, 2006	2006	Australia	30	58
Lenzen et al, 2006	2006	Australia	30	31
Lenzen et al, 2006	2006	Australia	30	9.1
Lenzen et al, 2006	2006	Australia	30	5.6
Lenzen et al, 2006	2006	Australia	30	120
Lenzen et al, 2006	2006	Australia	25	220
SDC, 2006	2006	Worldwide		2
SDC, 2006	2006	Worldwide		59
van Leeuwen and Smith, 2007	2006	Netherlands	100	112.6
van Leeuwen and Smith, 2007	2006	Netherlands	100	165.7
Tokimatsu et al., 2006	2006	Japan	60	10
Tokimatsu et al., 2006	2006	Japan	60	200
Lecointe et al., 2007	2007	Europe	60	6.1
Lecointe et al., 2007	2007	Europe	60	5.8
Lecointe et al., 2007	2007	Europe	60	5.5
Lecointe et al., 2007	2007	Europe	60	5.4
Lecointe et al., 2007	2007	Europe	60	5.2
Lecointe et al., 2007	2007	Europe	60	4.9
Lecointe et al., 2007	2007	Europe	60	4.6
Lecointe et al., 2007	2007	Europe	60	4.6
Lecointe et al., 2007	2007	Europe	60	4.4
Lecointe et al., 2007	2007	Europe	60	4.9
Lecointe et al., 2007	2007	Europe	60	4.2
Lecointe et al., 2007	2007	Europe	60	4
Lecointe et al., 2007	2007	Europe	60	3.9
Heede, 2009	2007	USA		2.5
Heede, 2009	2007	USA		5.7
Weisser, 2007	2007	Worldwide		2.8
Weisser, 2007	2007	Worldwide		24
Mallia and Lewis, 2013.	2008	Canada	40	4.8

Vattenfall, 2010a	2008	Sweden	50	5.1
Vattenfall, 2010a	2008	Sweden	50	5.7
Feng et al., 2014	2010	China		17.1
Poinssto et al., 2014	2010	Canada	50	5.3
WNA, 2011	2011	Worldwide		29
IPCC, 2011	2011	Worldwide		45
Nian et al., 2014	2012	Singapore	60	25
Warner and Heath, 2012	2012	Worldwide		12

Table A8. Data for life-cycle carbon emissions for wind power.

Reference	Data Year	Location	Life (Years)	Reported (gCO ₂ eq/kWh)
Chataignere and Le Boulch, 2003	2002	Europe	20	7.5
Chataignere and Le Boulch, 2003	2002	Europe	20	7.9
Chataignere and Le Boulch, 2003	2002	Europe	20	12
Chataignere and Le Boulch, 2003	2002	Europe	20	9.8
Chataignere and Le Boulch, 2003	2002	Europe	20	9.2
Chataignere and Le Boulch, 2003	2002	Europe	20	9.5
Vattenfall, 2003	2002	Sweden	40	10.3
Dones et al., 2005	2003	Germany	30	11
Dones, 2005	2003	Germany	30	13
Dones, 2007	2003	Swiss and European	30	9.6
Dones, 2007	2003	Swiss and European	30	14
Dones, 2007	2003	Swiss and European	30	12
Jungbluth et al., 2005	2003	Baltic sea	30	11
Enel SpA. 2004.	2004	Italy	20	17
Khan et al., 2005	2004	Canada	20	17
Rydh et al., 2004	2004	Sweden	20	7
Rydh et al., 2004	2004	Sweden	20	11
Spitzley and Keoleian, 2004	2004	Western USA	30	1.7
Spitzley and Keoleian, 2004	2004	Western USA	30	2.5
WEC, 2004	2004	Greece		8.2
WEC, 2004	2004	Finland		8.4
WEC, 2004	2004	Australia		12
WEC, 2004	2004	Denmark		15
WEC, 2004	2004	Denmark		22
Hondo, 2005	2005	Japan	30	15
Hondo, 2005	2005	Japan	30	20
Hondo, 2005	2005	Japan	30	21
Hondo, 2005	2005	Japan	30	27
Hondo, 2005	2005	Japan	30	30
Hondo, 2005	2005	Japan	30	40
Hondo, 2005	2005	Japan	30	49
Hondo, 2005	2005	Japan	30	72
Vestas Wind Systems A/S. 2006a	2005	Denmark	20	7
Vestas Wind Systems A/S. 2006b	2005	Denmark	20	4.7
Vestas Wind Systems A/S. 2006c	2005	Denmark.	20	5.3
Ardente et al., 2008	2006	Italy	20	14.8
Lee and Tzeng, 2008	2006	Taiwan	20	3.6
White, 2006	2006	USA	25	14
White, 2006	2006	USA	20	18
White, 2006	2006	USA	30	34
Dolan, 2007	2006	USA	20	24
Uchiyama, 2007	2006	Japan		9.5

Weisser, 2007	2006	Worldwide		18
Crawford, 2009	2008	Australia	20	31.9
Crawford, 2009	2008	Australia	20	34.8
DONG Energy, 2008	2008	North Sea	20	8.1
Government of Canada, 2010	2008	Canada		11
Mallia and Lewis, 2013.	2008	Canada	20	22
Rule et al., 2009	2008	New Zealand	100	3
Vattenfall, 2010	2008	Sweden	20	16
Vattenfall, 2010	2008	Sweden	20	17
Wagner et al., 2011	2008	Germany	20	32
Jacobson, 2009	2009	Japan	20	2.8
Jacobson, 2009	2009	Japan	30	4.2
Jacobson, 2009	2009	Japan	20	7.4
Jacobson, 2009	2009	Japan	30	11.1
Martínez et al., 2009	2009	Spain	20	6.2
Martínez et al., 2009	2009	Spain	20	6.6
Martínez et al., 2009	2009	Spain	20	9.3
Tremeac and Meunier, 2009	2009	Southern France	20	46.8
Tremeac and Meunier, 2009	2009	Southern France	20	12
Tremeac and Meunier, 2009	2009	Southern France	20	16
Tremeac and Meunier, 2009	2009	Southern France	20	21
Dotzauer, 2010.	2010	Swiss		10
Covenant of Mayors, 2010.	2010	Europe	20	9
Covenant of Mayors, 2010.	2010	Europe		11
Feng et al., 2014	2010	China		13.2
Kabir et al., 2012	2010	Canada	25	42.7
Kabir et al., 2012	2010	Canada	25	25.1
Kabir et al., 2012	2010	Canada	25	17.8
Wang and Sun, 2012.	2010	China	20	8.2
Arvesen and Hertwich, 2012	2011	Worldwide	20	22.5
Arvesen and Hertwich, 2012	2011	Worldwide	25	21.2
Raadal et al., 2011	2011	Worldwide		8.3
Vestas wind systems A/S, 2011	2011	Denmark	20	7
Wiedmann et al., 2011	2011	UK	20	13.4
Dolan and Heath, 2012	2012	Worldwide	20	11
Kuo, 2014.	2012	USA	20	11
IPCC, 2012	2012	Worldwide		12
Guezuraga et al., 2012	2012	Germany, Denmark, China	20	9.7
Guezuraga et al., 2012	2012	Germany, Denmark, China	20	8.8
Oebels and Pacca, 2013	2012	Northern Brazil	20	7.1
Querini et al., 2012	2012	Worldwide	20	12
Zimmermann and Gößling-Reisemanna, 2012	2012	Germany	20	7.9

Table A9. Data for life-cycle carbon emissions for solar power.

Reference	Data Year	Location	Life (Years)	Reported (gCO ₂ eq/kWh)
Tripanagnostopoulos, 2006	2002	Greece	100	54.7
Tripanagnostopoulos, 2006	2002	Greece	100	50.8
Tripanagnostopoulos, 2006	2002	Greece	100	61.8
Kannan et al., 2006	2003	Singapore	25	217
Kannan et al., 2007	2003	Singapore	25	165

Frankl et al., 2005	2004	Europe	25	79
Frankl et al., 2005	2004	Europe	25	42
Frankl et al., 2005	2004	Europe	25	88
Frankl et al., 2005	2004	Europe	25	47
Frankl et al., 2005	2004	Europe	25	83
Frankl et al., 2005	2004	Europe	25	45
Frankl et al., 2005	2004	Europe	25	81
Frankl et al., 2005	2004	Europe	25	43
Frankl et al., 2005	2004	Europe	25	64
Frankl et al., 2005	2004	Europe	25	34
Frankl et al., 2005	2004	Europe	25	72
Frankl et al., 2005	2004	Europe	25	39
Frankl et al., 2005	2004	Europe	25	47
Frankl et al., 2005	2004	Europe	25	69
Frankl et al., 2005	2004	Europe	25	64
Frankl et al., 2005	2004	Europe	25	35
Fthenakis et al., 2006	2005	Europe	30	45
Fthenakis et al., 2006	2005	Europe	30	36.4
Fthenakis et al., 2006	2005	Europe	30	30
Hondo, 2005	2005	Japan	30	53
Muneer et al., 2006	2005	UK	30	44
Pacca et al., 2006	2005	USA	20	36
Pacca et al., 2006	2005	USA	20	72.4
Raugei et al., 2007	2005	South-Europe	20	72
Raugei et al., 2007	2005	South-Europe	20	95
Alsema et al., 2006	2006	South-Europe	30	35
Alsema et al., 2006	2006	South-Europe	30	45
Alsema et al., 2006	2006	South-Europe	30	30
Lenzen, 2008	2006	Australia	30	53
Fthenakis and Kim, 2008	2006	USA	30	26
Fthenakis and Kim, 2008	2006	USA	30	38
Pacca et al., 2007	2006	USA	20	34.2
Pacca et al., 2007	2006	USA	20	72.4
Ito et al., 2010	2007	Desert area		50
Ito et al., 2010	2007	Desert area		43
Dominguez-Ramos et al., 2010	2007	Spain	25	27
Dominguez-Ramos et al., 2010	2007	Spain	25	33
Dominguez-Ramos et al., 2010	2007	Spain	25	36
Dominguez-Ramos et al., 2010	2007	Spain	25	30
Fthenakis et al., 2009	2008	USA	30	29.5
Fthenakis et al., 2009	2008	USA	30	22
Fthenakis et al., 2009	2008	USA	30	30
Ito et al., 2008	2008	Desert area	30	57
Ito et al., 2008	2008	Desert area	30	44
Ito et al., 2008	2008	Desert area	30	34
Ito et al., 2008	2008	Desert area	30	47
Lu and Yang, 2010	2008	Hong Kong	30	68
SENSE, 2008	2008	Europe	30	43
de Wild-Scholten, 2009.	2008	South-European	30	30
Held and Ilg, 2011	2009	North Germany	30	50
Held and Ilg, 2011	2009	North Germany	30	38
Held and Ilg, 2011	2009	South-Europe	30	30
Held and Ilg, 2011	2009	South-Europe	30	23
de Wild-Scholten, 2013	2011	South-Europe	30	27.2

de Wild-Scholten, 2013	2011	South-Europe	30	49.1
de Wild-Scholten, 2013	2011	South-Europe	30	38
de Wild-Scholten, 2013	2011	South-Europe	30	81
Bensebaa, 2011	2011	Spain	30	30
Klein and Rubin, 2013	2011	USA	30	72
Klein and Rubin, 2013	2011	USA	30	60
Louwenet al., 2015	2012	Europe	30	38
Kuo, 2014.	2012	USA	30	18
IPCC,2012	2012	Worldwide		46
De Feo et al., 2016.	2012	Italy	100	18.8
Barton, 2014.	2012	Australia	30	18
Barton, 2014.	2012	Australia	30	37

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Chapter 6

General discussion

6.1. Introduction

As indicated in Chapter 1, LE technologies have a significant potential to reduce the total carbon emissions in China. Yet, in existing research, most authors analyzed such implications for China as a whole rather than the amount of carbon embodied in the products and services for China's exports. We took a regional approach, since the implementation of LE and the production of products and services for China's exports very heterogeneously distributed over the various Chinese regions. Current studies also tend to neglect the carbon emissions related to the investments in LE. Against this background, Chapter 1 formulated 4 research questions which were addressed in the following 4 chapters. Since we wanted to take into account regional differences in the electricity and industrial production structures of China, MRIO was used as a core methodology. In this way, inter-regional linkages and spillovers could be covered. Since the available Chinese MRIO does not distinguish different electricity production techniques, another contribution of this thesis was constructing a hybrid MRIO that discerns individual energy technologies.

In the next section, we want to answer the research questions posed in the introduction. Section 6.3 provides some methodological reflections and discussions. Section 6.4 then concludes with an outlook.

6.2. Answers to the research questions

6.2.1. Carbon emissions in China

Research question 1 was formulated as follows.

1. *How are carbon emissions distributed across sectors from the perspective of inter-sectoral linkages? What spillovers occur via supply chains, particularly between the electricity sector and other production sectors?*

The analysis of multi-sectoral carbon emissions in China has become a hot issue. Yet, the analysis of inter-sectoral production linkages including spillover and feedback emissions have received little attention. Applying an extended, IO-based, time-series decomposition approach to analyze inter-sectoral carbon relationships allowed us to gain a better understanding of each sector's role on national carbon emissions. By tracing the four emission components (direct, internal, spillover and feedback), key sectors and relevant carbon transactions were identified, allowing for a characterization of the patterns of sectoral emissions in China.

Among the 26 economic sectors analyzed, the sectors of electricity and heavy manufacturing were key sectors in output-induced carbon emissions, while the equipment manufacturing, construction, and services sectors were the key emission sectors from the perspective of demand. Spillover components of the equipment manufacturing, construction, and services sectors were largely responsible for the rapid carbon emission growth in the electricity and heavy manufacturing sectors. Therefore, carbon emissions in

China were mainly transferred from the basic industrial sectors (e.g. electricity sector) to the equipment manufacturing, construction and services sectors. The electricity sector also ranked top in the feedback component shares, which means that the intermediate inputs of many economic sectors depend on the production of electricity sector. Since the production of upstream sectors (e.g. electricity sector) increased the total energy consumption and total carbon emissions, the design of policies to control the carbon emissions in the electricity sector would help to reduce a large part of carbon emissions in China. Moreover, the internal component of the electricity sector was larger than that of other sectors. This implies that the internal efficiency and production structure changes in the electricity sector were the most important factors in curbing its rising trend of carbon emissions. Therefore, developing low-carbon electricity (LE) is conducive to reducing the carbon emissions in the electricity sector and to consequently achieving the goal of carbon emission reduction in China.

6.2.2. LE development and carbon emissions in exports

Research question 2 was formulated as follows:

2. *How will the development of low-carbon energy across regions impact carbon emissions embodied in China's exports? What is the role of electricity transmission and supply chains in regional emission reductions?*

Comparing the historical LE expansion against a counterfactual in which the LE expansion of 2002-2014 did not take place, shows that the ongoing transition of China toward LE has substantially contributed to reducing carbon emissions embodied in China's exports, resulting in a net emissions reduction of 203 Mt (11.5% of the total carbon emissions embodied in exports), 244 Mt (14.9%), and 259 Mt (19.5%) in 2007, 2010 and 2014, respectively.

Since there are significant differences across regions in China, it is essential to compare the regional effects of LE development on the carbon emissions embodied in exports. A multi-regional investigation shows that the carbon impact of LE expansion generally followed the regional distribution of export-embodied emissions, because most provinces with great LE impacts were mainly affected by the intra-regional effect, and the intra-regional effects matched up well with LE resource across regions in China. Jiangsu, Zhejiang, and Guangdong, the important trade provinces in China, had the largest carbon emission reductions. However, Hebei and Shandong had a relatively smaller carbon impact of LE development than Sichuan and Hubei, even though their export-embodied emissions were larger. This is because wind power played an important role in alleviating carbon emissions in Hebei and Shandong, while the proportion of wind power in electricity mix was still low. In contrast, Sichuan and Hubei faced the greatest increases in hydropower generation such that the LE effects in these two regions became much larger.

Given the existence of inter-regional linkages, there were three district modes regarding the carbon impacts of LE expansion: the intra-regional effect, the electricity transmission effect and the supply-chain effect. In total, electricity transmission infrastructure led to emission reductions of 50 Mt in 2007, increasing to 62 Mt in 2014. Regionally, the exported electricity in the central and southwestern regions showed significant effects on alleviating the emissions in the eastern and southern regions. The exported electricity in the northwestern region also had a positive effect on reducing the carbon emissions in the

northern region. Specifically, electricity transmission was responsible for the very large embodied-carbon savings in Shanghai, which comprised over 48% of the total LE impacts in Shanghai from 2007 to 2014. The significant penetration of LE in adjacent provinces was necessary to reduce export-embodied carbon emissions in Hebei. In 2014, the electricity transmission effect in Hebei comprised 40.1% of the total carbon impact of LE development.

In addition to the electricity transmission effect, the carbon impact of LE development was influenced by the supply-chain effect. The supply-chain effect resulted in a maximum reduction of 41 Mt in 2010, then dropped to net savings of 39 Mt in 2014. The comparatively high share of supply-chain effects in the southern and eastern regions was attributable to the LE development in the central and western regions. This was because the coastal regions, which suffer chronic resource shortages, depend strongly on the supply of energy and materials from the western and central regions. The supply-chain effect was particularly large for Shanghai and Hebei, in which the supply-chain effect shares were, respectively, 49% and 38% in 2014. Moreover, the impact of LE development on the carbon flows from neighboring provinces to Hebei and Shanghai could be utilized efficiently to reduce the export-embodied carbon emissions in Hebei and Shanghai. This calls for a significant improvement in the electricity mix in the surrounding regions of Hebei and Shanghai.

6.2.3. Carbon impacts related to investments in LE technologies

Research question 3 was formulated as follows:

3. *How do the carbon emissions from investments in LE infrastructure compare to the reduction of carbon emissions during the use of LE? How are the carbon impacts of this infrastructure distributed within China?*

A comparison between historical emissions and a counterfactual scenario shows the total operational impact of LE drove increasing mitigation of emissions of 48.84 Mt, 81.83 Mt and 129.48 Mt CO₂ in 2002, 2007 and 2010, respectively. However, electricity investment activities also have short-term effects on carbon emissions from other sectors, for example shaping the carbon emissions of construction and manufacturing. Since LE infrastructure tends to have higher upfront inputs than fossil-fuel electricity in the infrastructure stage, China's LE investments drove a net emission increase of 16.21 Mt in 2002, 28.71 Mt in 2007 and 46.29 Mt in 2010.

The carbon impact of LE investments exhibited significant regional differences, as the carbon intensity of LE installation was not uniform across all regions in China. The magnitude of net impacts of LE investments in Guangdong, eastern and southwestern provinces, which are endowed with hydro and nuclear power resources, was smaller than that of net operational impact of LE. However, in several northern, northeastern and northwestern provinces (e.g. Gansu and Inner Mongolia), with abundant wind power resources, the net emission reductions from LE operation could not offset their net emission increases from LE investments for the period examined.

Also, as MRIO models captured the emissions associated with any intermediate inputs between regions, the inter-regional spillover effects of LE investments could be identified. The majority of carbon emissions from LE investments in the developed eastern region resulted from the inter-regional spillover effect. This means that the carbon impact of LE

investments was moved from downstream regions to upstream regions, as the developed eastern region depends heavily on the intermediate inputs from the western and central regions.

6.2.4 Projected carbon impacts from the expansion of LE infrastructure

Research question 4 was formulated as follows:

4. *How will the carbon impact from the expansion of LE infrastructure evolve in the future?*

Mitigation scenarios reported by international (IEA) and national (NDRC) bodies, which are used to investigate how carbon emissions reductions can be achieved, usually show a substantial contribution of the LE expansion in the electricity sector. However, the carbon overheads from the expansion of LE infrastructure may have negative implications for the effectiveness of the carbon emission reductions from LE operation in the future. Thus, it is important to derive a projection of the carbon impact of the expansion of LE infrastructure.

Due to learning effects, the carbon intensity of LE installation decreases as the electricity sector installs more capacity. This is because LE sectors learn how to build infrastructure more efficiently, often termed an experience curve. The carbon impact of LE investments over time were based on the experience curve of historical data, which was projected forward using the future capacity in the scenarios of IEA and NDRC. The projected results indicate that, during 2015-2040, the carbon emissions associated with the expansion in LE infrastructure will not represent more than 4% of the projected total carbon emissions in the same year. In the IEA-sustainable development scenario, the total carbon emissions are lower, and the annual average carbon impact of LE investments was less than 2% of the total carbon emissions up to 2040. Out of all the scenarios examined, the IEA-sustainable development scenarios led to the highest carbon reductions. Despite the fact that LE investments increase rapidly in the NDRC-High Renewable Penetration scenario, the carbon impact of LE infrastructure expansion will peak during 2030-2035 and decrease thereafter. Overall, the result shows that it is necessary to take into account the carbon impact of LE investments, but it should not be considered an argument to halt the development of LE.

6.3. General discussion

As discussed in Chapter 1, a key obstacle to previous research was the lack of detail on LE technologies in the existing Chinese MRIO tables. The economic-energy hybrid, MRIO model proposed in Chapter 3 helped to solve this problem. Therefore, it is essential to discuss the advantage of this model and its possible contribution to future studies. Chapter 4 showed the regional differences in the expansion in LE infrastructure, from which policy implications need to be discussed. Finally, although a multi-regional carbon impact of LE development in China was developed, the thesis still has certain uncertainties need to be highlighted.

6.3.1. A disaggregation of carbon impact of LE development

The primary contribution of Chapter 3 was to introduce a novel economic-energy hybrid, MRIO model. This model is based on a model of primary energy use from Guevara and Rodrigues (2016). Compared to conventional MRIO models, the hybrid model has a

detailed description of carbon flows based on energy in physical units and non-energy production processes of the economy in monetary units. It characterizes the vector of the total carbon emissions as a function of six driving forces (carbon intensity of primary energy, electricity mix, electricity transmission, electricity intensity, economic structure and final demand), which can improve the conclusions obtained within the conventional MRIO framework. Moreover, since the electricity sector in most MRIO tables is highly aggregated, the proposed model could provide better insights to the carbon impact of LE development by investigating energy use mechanisms in the economy. Specifically, it extends MRIO application to the consideration of inter-regional electricity transmission and economic linkages between regions, such that the estimation of the carbon impact of LE development is more accurate.

Additionally, based on this novel model for China, Chapter 3 compared a counterfactual scenario without LE expansion against the historical LE expansion. Then, within a theoretical framework that combined the economic-energy hybrid MRIO model and scenario analysis, a decomposition analysis could be performed to obtain more detailed insights into the core mechanism for the carbon impact of LE development. The carbon impact of LE development was systemically calculated by categorizing intra-regional effect, electricity transmission effect and supply-chain effect. Thus, not only the effect of intra-regional LE development, but also the inter-regional impact, which is supported by the electricity transmission system or wide economic linkages, could be identified. In such case, the electricity transmission system is one way in which the carbon impact of LE from a region to other regions. Meanwhile, the carbon impact of LE development also can occur along the entire supply chains in export-related goods and services. These are essential in determining which region's LE development have the greatest potential for emission mitigation.

6.3.2. Intra-regional and inter-regional effects of LE investments

Chapter 4 established a comprehensive analytical framework to explore the carbon impact of LE investments. It offered an MRIO approach for comparing the carbon impact of LE investments with the operational impact of LE development. MRIO models were used to quantify the carbon impact of LE investments from consumption-based perspective considering both intra-regional and inter-regional impacts. The intra-regional impact shows that the expansion of domestic LE infrastructure had a strong effect on embodied carbon emissions in each region, while the spillover effect further clarified the impact of LE investments on inter-regional carbon flows along the supply chain. The method presented could be helpful for the macro-analysis of carbon impacts of LE investments in China on the regional level.

The results show the regional characteristics of carbon impact of LE investments, which is valuable for decision making of emission reduction strategies. The intra-regional carbon impact took up a large proportion of the total carbon impact in the western and central regions, whereas a large inter-regional spillover impact can be found for the eastern region. Moreover, the analysis of carbon flows shows that the western and central regions had the largest outflows and the eastern region was the largest receiver. This means that the eastern region used more intermediate products provided by the western and central regions to satisfy its demand for LE infrastructure, such that the corresponding emissions occurred in the western and central regions through a spillover effect in the supply chain of the eastern region. This phenomenon is similar to the findings of Yan et

al., (2017) and Meng et al., (2017). Thus, the technological improvements in the manufacturing in the western and central regions can not only help reduce their own carbon impacts of LE investments, but also decrease the carbon impact of LE investments in the eastern region. Moreover, a region tends to transfer its impact of LE infrastructure to neighboring regions. Feng et al., (2014)'s studies provided a possible explanation for this phenomenon, which argued that a region tends to consume more intermediate inputs from neighboring regions due to transportation costs, thus transfers more emissions to neighboring regions.

6.3.3. Uncertainty

In order to derive the estimates of carbon impacts of LE investments in Chapter 4, a demand-driven MRIO model (Hedi, 2016) was developed, which will necessarily induce a variety of uncertainty due to its top-down nature. First, some assumptions were applied due to the lack of relevant statistical data. For example, the investment cost structure of an electricity technology for different periods and regions was assumed to be identical, which should be improved in the future along with the enrichment of data source. Second, the effect of sectoral aggregation in the MRIO framework may give biased results, as emission data refer to the average of sub-products in the broader sector (Su et al., 2010, Zafrilla et al., 2014). Thus, more detailed disaggregations could further enhance the calculation's accuracy and reliability. Third, due to data limitations, the estimate of carbon emissions was based on fossil fuel combustion and cement production. However, Wiedmann et al, (2011) have highlighted that, in order to more accurately assess the impact of LE infrastructure, carbon emissions from plastics can be included.

Moreover, Chapter 5 applied experience curves to project the trend of carbon impacts from LE investments. The concept of experience curves provides a transparent tool to contrast the production capacity and reduction potential of carbon emissions from LE installation. However, this method does not consider other important constraints. For example, more LE investments, would result in an electricity sector with lower emissions in the operation phase, which might decrease the carbon emissions from LE investments, as LE investment activities are supported by the production of the electricity sector itself via feedback effect. However, the carbon intensity of electricity generation has become relatively stable in recent years, such that the effect of electricity sector itself on LE investments would tends to reduce in future years. Thus, using the experience curve without considering carbon intensity of electricity generation is a reasonable approximation.

6.3. Outlook

There are still at least three important questions which need answering in future work.

First, although the analysis in Chapter 3 covers the impact of LE development on the export-embodied carbon emissions at the regional level, the impact of China's LE development on carbon emissions in specific trade countries/regions has not been explored. Liu et al., (2015) has argued that the changes in primary energy consumption in some targeted provinces could drastically reduce global emissions. Thus, the impact of LE development on specific carbon leakage between China and a major trade country is worthy of further attention. Moreover, consumption-based accounting can be used as an alternative carbon accounting method, so an interesting future analysis would be

investigating the impact of LE development on carbon leakage between China and specific developed countries in the context of global value chain.

Second, in Chapter 4, the accuracy of the estimated carbon impact of LE investments depends on the aggregation level of the economic activities in MRIO tables. Further research would be needed to link detailed process-specific information to the MRIO model in order to improve accuracy of estimates.

Finally, although Chapter 5 have offered an approach to predict the reduction of the carbon overhead of LE infrastructure up to 2040 using experience curves, we were unable to account for the fact that LE expansion will reduce the operational carbon emissions. That is, the operational impact of LE development in the future has not been explored. Thus, future research could give more insights into the ex-ante projections of operational impact of LE development.

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Summary

Introduction

China is currently the largest CO₂ emitter in the world. The electricity sector plays a very important role in China's carbon emissions growth. Whether the electricity sector can successfully improve electricity mix is related to the future of China's carbon emissions targets. Therefore, there is an urgent need to develop low-carbon electricity (LE) technologies for electricity generation. Great efforts to develop LE have been made in China and great advancement has been obtained on hydro, nuclear, wind and solar power expansion. A substantial number of studies have explored the impact of LE development on the total carbon emissions in China. However, given the difference of economic development and resource endowments between regions in China, the carbon impact of LE development shows regional heterogeneity. Therefore, an obvious gap exists in systematically assessing the carbon impact of LE at the regional level, especially in terms of carbon emissions embodied in China's exports. Moreover, there is a lack of investigation of the carbon impact of LE investments, which can further highlight the long-term potentiality of emission mitigations of LE development.

Research questions

From the above, we can deduce a number of issues. First, as many authors have shown, the structure of China's energy system has enormous implications on the carbon embodied in the products and services produced and used in and exported by China. So, a study of the impact Chinese LE development on export-embodied carbon emissions should contribute to providing fundamental information for investigating export-embodied emission reduction potentials in China. Yet, few authors have taken into account LE developments from a regional perspective in China. A main reason for this is lack of detail in the electricity production sector in the available Chinese MRIO tables. However, this problem can be solved by a hybrid unit MRIO mode (see Chapter 3) and a final demand approach (see Chapter 4), as described above. At the same time a regional perspective is highly relevant, since the implementation of LE and the production of products and services for use in China and for exports are not at evenly distributed over the various Chinese regions. It is also appreciated that LE investments are usually more carbon intensive than investments in traditional electricity generation. As indicated, most scenarios do not take this factor into account (e.g. IEA, (2017)), let alone from a region-specific perspective. Against this background, this thesis aims to answer the following research questions:

1. *How are carbon emissions distributed across sectors from the perspective of inter-sectoral linkages? What spillovers occur via supply chains, particularly between the electricity sector and other production sectors?*
2. *How will the development of low-carbon energy across regions impact carbon emissions embodied in China's exports? What is the role of electricity transmission and supply chains in regional emission reductions?*
3. *How do the carbon emissions from investments in LE infrastructure compare to the reduction of carbon emissions during the use of LE? How are the carbon impacts of this infrastructure distributed within China?*

4. *How will the carbon impact from the expansion of LE infrastructure evolve in the future?*

Answers to research questions

Answers to RQ1: Chapter 2 developed a subsystem input-output model to investigate the temporal and sectoral changes of multi-sectoral carbon emissions in China from 1997 to 2012. Comparing demand-induced carbon emissions with output-induced carbon emissions produced several useful conclusions. Moreover, the total carbon emissions were decomposed into four components: internal, spillover, feedback, and direct components. The results show that, the output-induced emissions of the electricity sector were largest, accounting for 40.1% and 49.3% of the total in 1997 and 2012 respectively, while the construction sector tended to have the largest demand-induced carbon emissions. The electricity sector was responsible for the outflows of carbon emissions, as the equipment manufacturing, construction and services sectors had a spillover effect on the carbon emissions in the electricity sector via inter-sectoral linkages.

Answers to RQ2: In order to attain information on the impact of LE on export-embodied carbon emissions, the Chapter 3 applied a hybrid, energy-economic, multi-regional input-output (MRIO) model of China and compared the observed LE development against a connatural scenario without LE expansion. A decomposition impact assessment framework was used to divide the total LE impact into three effects: intra-regional effect, electricity transmission effect, and supply-chain effect. The results show LE development reduced carbon emissions embodied in exports by 203 Mt (11.5% of the total carbon emissions embodied in exports), 244 Mt (14.9%), and 259 Mt (19.5%) in 2007, 2010 and 2014, respectively. Most important trade provinces in China, Jiangsu, Zhejiang and Guangdong, had the largest carbon emissions reductions. However, given the substantial hydropower development, some southwestern provinces (e.g. Sichuan and Hubei) had relative larger carbon impacts of LE than some major trade provinces (e.g. Hebei and Shandong). The exported electricity in the central and southwestern regions made a great contribution to reduce the carbon emissions in the eastern and southern regions via inter-regional electricity transmission and economic linkages.

Answers to RQ3: Many LE analyses neglected the impact of the expansion in LE infrastructure on carbon emissions. A demand-driven MRIO model was proposed in the Chapter 4 to estimate the carbon impact of LE investments at the regional level from both the intra-regional and inter-regional perspectives. Moreover, the carbon impact of LE investments was compared with the operational impact of LE development. The results show that the expansion of LE infrastructure increased net carbon emissions of 16.21 Mt, 28.71 Mt and 47.29 Mt in 2002, 2007 and 2010 respectively, even though the operation of LE was conducive to decreasing carbon emissions of 48.84 Mt, 81.83 Mt and 129.48 Mt per year. The magnitude of net operational impact of LE in the southwestern and eastern provinces was larger than that of net impact of LE investments. However, the decreased carbon emissions due to the operational impact of LE in several northern, northeastern and northwestern provinces cannot offset the increased carbon emissions due to LE investments. Moreover, the intra-regional effect of LE investments in the inland regions were large, while a large spillover effect could be found in the developed eastern region.

Answers to RQ4: The trend of cumulative installed capacity of LE in China have been projected by the well-known scenarios from national and international bodies. However,

the future carbon impact of LE development is influenced by the carbon impact of the expansion of LE infrastructure, as LE infrastructure tends to require more materials than fossil-fuel electricity generation technologies. In Chapter 5, the carbon overhead from LE infrastructure expansion was projected using available scenarios and experience curves of historical carbon intensity of LE installation. The projection shows that in all the scenario, the percentage of annual average carbon impact of LE investments in the China's total carbon emissions will be less than 4% during 2015-2040. The carbon impact of LE investments in the all IEA scenarios will decline steadily during 2015-2040. Moreover, the carbon impact of LE investments in the NDRC-High Renewable Energy Penetration scenario will peak during the period 2030-2035, such that the carbon impact of LE investments in all scenarios will reach their lowest level during 2035-2040.

Outlook

The standard Chinese MRIO has a problem of low sector disaggregation, such that it is difficult to investigate the carbon impact of region-specific LE development in China. Moreover, neglecting the effect of electricity transmission results in omitting the transfers of LE impacts. These drawbacks are solved by a hybrid MRIO model, which links the LE generation in energy units to the Leontief matrix in monetary units and includes electricity transmission into the calculation of LE impact. The Chinese hybrid MRIO provides many options for further study (e.g. structural decomposition analysis). It also can be connected to global MRIO tables (e.g. EXIOBASE database). Therefore, future efforts could be made to analyze the impact of LE development on carbon leakage between China and specific developed countries in the context of global value chain.

Within a demand-driven MRIO model, the intra-regional impact and inter-regional impact of LE investments were used to show the differences in the regional pattern of the carbon impact of the expansion of LE infrastructure. However, the demand-driven MRIO model, which allocates the inputs of LE investments to the sectors existing in the MRIO table by constructing a demand vector, may induce a sector aggregation error. Therefore, further research is suggested to link detailed process-specific information to the MRIO model in order to improve accuracy of estimates.

The projection of the carbon impact of LE investments has risen policy implications for future LE development. However, experience curve induced a certain uncertainty, as the one-factor experience curve may be influenced by the future decline of the carbon intensity of electricity generation. Thus, for the future carbon impact of LE investments, the key question is whether the historical carbon intensity of electricity generation will be stable in the future. The answer to this question will depend on future operational impact of LE development on carbon emissions. Therefore, future research could give more insights into the ex-ante projections of operational impact of LE development.

Samenvatting

Inleiding

China is momenteel de grootste bron van CO₂ emissies ter wereld. De elektriciteitssector speelt een belangrijke rol in de groei van deze CO₂ emissies. De vraag of de elektriciteitssector de emissiedoelen van China kan halen is gerelateerd aan de vraag of de elektriciteitsmix in de toekomst kan worden verbeterd. Er is daarom een grote behoefte om CO₂-arme technologieën voor elektriciteitsproductie te ontwikkelen (zogenaamde LE: Laag CO₂ elektriciteitsproductie). China heeft zich aanzienlijke inspanningen getroost om LE in te voeren, gebaseerd op waterkracht, nucleaire energie, en wind- en zonne-energie. Een groot aantal studies heeft het effect van de implementatie van LE op de CO₂ emissies in China onderzocht. Echter, omdat het potentieel voor LE en de distributie van economische bedrijvigheid verschillend zijn tussen regio's in China, verschilt de impact van LE per regio. Er is dus behoefte om de impact van LE op CO₂ emissies op regionaal niveau te analyseren, en met name dan de impact in termen van de CO₂ voetafdruk van de Chinese export vanuit een specifieke regio. Er is verder een gebrek aan analyses van de CO₂ voetafdruk van investeringen in LE, van belang om de lange termijn emissiereducties als gevolg van de implementatie van LE goed te bepalen.

Onderzoeksvragen

Bovenstaande inleiding leidt tot een aantal punten van aandacht. Ten eerste, zoals veel andere auteurs al hebben onderzocht, heeft de structuur van China's energiesysteem een enorme invloed op de CO₂ voetafdruk van de producten en diensten geproduceerd, gebruikt en geëxporteerd door China. Een studie over de implementatie van LE in China kan dus aangeven hoe deze CO₂ voetafdrukken kunnen worden verminderd. Echter, vrijwel geen enkele auteur heeft gekeken naar de implementatie van LE vanuit een regionaal perspectief en de voetafdruk van productie op regionaal niveau. De belangrijkste reden voor dit is het gebruik aan detail in de Chinese Multi-regionale Input Output (MRIO) tabellen ten aanzien van elektriciteitsproductie. Dit proefschrift lost dat probleem op door een hybride MRIO te ontwikkelen (zie hoofdstuk 3), en een analyse vanuit de finale vraag toe te passen (hoofdstuk 4). Daarnaast is ook een regionaal perspectief heel relevant, omdat de implementatie van LE en de productie van producten en diensten voor export en gebruik in China niet gelijk zijn verdeeld tussen de verschillende Chinese regio's. Verder is het zo dat investeringen in LE in het algemeen meer CO₂-intensief zijn als investeringen in traditionele elektriciteitsproductie. De meeste bestaande scenariostudies nemen zulke verschillen niet in ogenschouw (b.v. IEA, 2017), en al helemaal niet vanuit een regionaal perspectief. Tegen deze achtergrond richt dit proefschrift zich op de volgende onderzoeksvragen (OV).

1. *Hoe zijn CO₂ emissies verdeeld over economisch sectoren, gezien vanuit het perspectief van intersectorale verbindingen? Welke spillovers vinden plaats via diverse waardenketens, vooral tussen de elektriciteitssector en de andere productiesectoren?*
2. *Hoe beïnvloedt de implementatie van LE de CO₂ voetafdruk van de exporten van China? Wat is de rol van interprovinciale waardenketens en transmissie van elektriciteit in regionale reducties van emissies?*

3. *Hoe verhouden de emissies van investeringen in LE zich tot de reductie van emissies gedurende het gebruik van LE? Hoe is de CO₂ voetafdruk van investeringen in LE verdeeld over China?*
4. *Hoe ontwikkelt de CO₂ voetafdruk van uitbreiding van LE infrastructuur zich in de toekomst?*

Antwoorden op de onderzoeksvragen

Antwoord op OV 1: Hoofdstuk 2 ontwikkelt een input-output model dat de verandering van CO₂ emissies per sector en in de tijd in China analyseert, van 1997 tot 2012. Een vergelijking van de CO₂ voetafdruk van consumptie en de directe CO₂ emissies van productie leidt tot een aantal conclusies. De CO₂ emissies zijn uitgesplitst in vier componenten: intern, spillover, feedback, en directe. De resultaten laten zien dat de emissies van de elektriciteitssector het hoogste zijn, te weten 40.1% en 49.3 van het totaal in 1997 en 2012. De bouwsector had de hoogste vraag-geïnduceerde CO₂ emissies. Via inter-sectorale relaties hadden de bouwsector, de service sector en de machinebouw een belangrijk spillover effect op de emissies van de elektriciteitssector.

Antwoord op OV2: Om inzicht te krijgen op de invloed van LE op de CO₂-voetafdruk van de export van China, ontwikkelt Hoofdstuk 3 een hybride energie-economisch Multi-Regionaal Input Output (MRIO) model. Vervolgens is een scenario met implementatie van LE vergeleken met een scenario zonder uitbreiding van LE capaciteit. Het hoofdstuk gebruikt een decompositie benadering om de totale impact van LE op te splitsen in drie effecten: een intra-regionaal effect, een elektriciteits-transmissie-effect, en een waardeketen effect. De analyse geeft aan dat implementatie of LE de CO₂-voetafdruk van exporten in China verminderde met 203 Mt (11,5% of de totale CO₂ voetafdruk van export), 244 Mt (14,9%) en 259 Mt (19,5%) in respectievelijk 2007, 2010 en 2014. De provincies Jiangsu, Zhejiang and Guangdong, het meest van belang voor de export van China, hadden de grootste emissiereducties. Echter, enkele provincies in het Zuid-Westen van China (e.g. Sichuan en Hubei) kenden dankzij een flinke uitbreiding van de capaciteit voor waterkracht een hogere reductie van emissies dan enkele provincies (b.v. Sichuan en Hubei) met hoge exporten. De elektriciteit geëxporteerd uit de centrale en Zuid-westelijke regio's droeg in belangrijke mate bij tot de reductie van CO₂ emissies in de Oostelijke en Zuidelijke regio's via interregionale elektriciteitstransmissies en economische waardenketens.

Antwoord op OV3: Veel analyses rond LE negeren het feit dat uitbreiding van LE additionele CO₂ emissies kan veroorzaken. Hoofdstuk 4 gebruikt een MRIO model om de CO₂ voetafdruk van investeringen in LE te bepalen vanuit een intra- en inter-regionaal perspectief. Hoofdstuk 4 vergelijkt verder de CO₂ voetafdruk van investeringen in LE met lagere operationele emissies van LE in de gebruiksfase in vergelijking met traditionele elektriciteitsopwekking. De resultaten geven aan dat uitbreiding van LE infrastructuur de CO₂ emissies heeft verhoogd met 16.21 Mt, 28.71 Mt en 47.29 Mt in respectievelijk 2002, 2007 en 2010. Echter, dankzij de uitbreiding van LE stootte de elektriciteitssector in die jaren 48.84 Mt, 81.83 Mt en 129.48 Mt minder CO₂ uit. In de Zuidwestelijke en Oostelijke provincies was deze operationele vermindering van CO₂ emissies belangrijk groter dan de CO₂ voetafdruk van investeringen in LE. In de Noordelijke, Noordoostelijk en Noordwestelijke provincies was dit niet het geval. Verder werd duidelijk dat het intraregionale effect van investeringen in LE in de binnenlandse regio's hoog was, terwijl

een belangrijk spillover-effect gevonden kon worden in de meer ontwikkelde Oostelijke regio's.

Antwoord op OV4: Er is een inschatting gemaakt van de cumulatieve geïnstalleerde capaciteit van LE in China, gebruik makend van scenario's van diverse nationale en internationale organisaties. Zoals al geconstateerd in de analyse van Hoofdstuk 3, is de CO₂ voetafdruk van investeringen in LE hoger dan die van investeringen in traditionele technieken voor elektriciteitsopwekking. In de tijd neemt deze 'carbon overhead' echter af – bij uitbreiding van capaciteit kunnen nieuwe technieken zoals LE dankzij leereffecten steeds efficiënter worden geproduceerd. Hoofdstuk 5 bepaalt deze 'carbon overhead' op basis van leercurves ten aanzien van de CO₂-intensiteit van investeringen in LE in China, in combinatie met scenario's voor uitbreiding van de LE capaciteit. Deze analyse laat zien dat de gemiddelde jaarlijkse CO₂ emissie veroorzaakt door investeringen in LE minder dan 4% zal zijn van China's CO₂ emissies in de periode van 2015-2040. Verder zal in de scenario's gebaseerd op werk van de International Energy Agency (IEA) de CO₂-voetafdruk van investeringen in LE gestaag dalen in deze periode. In het Chinese 'NDRC-High Renewable Energy Penetration scenario' zal de CO₂-voetafdruk van investeringen in LE het hoogste zijn in de periode 2030-2035, om snel te dalen in de periode 2035-2040.

Vooruitblik

De bestaande Chinese MRIO tabel is erg geaggregeerd, wat het lastig maakt om de invloed op CO₂ emissies van regio-specifieke ontwikkelingen met betrekking tot LE goed te analyseren. Zo is er maar één sector voor elektriciteitsproductie, waardoor verschillende technieken voor het opwekken van elektriciteit niet kunnen worden onderscheiden. Ook wordt de transmissie van elektriciteit tussen provincies niet meegenomen. Dit proefschrift heeft deze problemen opgelost door een hybride MRIO model te ontwikkelen, dat productie van elektriciteit met LE uitgedrukt in energie-eenheden verbindt met de Leontief matrix in monetaire eenheden, en ook de transmissie van elektriciteit tussen provincies omvat. Dit Chinese hybride MRIO model geeft veel mogelijkheden voor nieuwe analyses, naast degenen die in dit proefschrift zijn toegepast. Het model kan ook worden verbonden aan globale MRIO tabellen (b.v. de EXIOBASE database). Dit maakt het bijvoorbeeld mogelijk om de specifieke invloed van investeringen in LE in China op de 'carbon leakage' tussen China en specifieke andere ontwikkelde landen te onderzoeken.

Het MRIO model is gebruikt om de intra-regionale en inter-regionale impacts van investeringen in LE op regionale schaal te analyseren. Echter, het vraaggedreven MRIO model, dat de CO₂ voetafdruk van investeringen in LE berekent op basis van inputs vanuit andere sectoren voor de productie van LE, kan wegens de hoge aggregatie van de MRIO tabel een aggregatiefout veroorzaken. Daarom wordt verder onderzoek aanbevolen waarin gedetailleerde, proces-specifieke informatie aan het MRIO model wordt toegevoegd om meer accurate resultaten te verkrijgen.

Dit proefschrift heeft verder de toekomstige CO₂ voetafdruk van investeringen in LE ingeschat. Echter, de leercurves die hier zijn gebruikt kunnen nog worden verfijnd. Hier is aangenomen dat de (wijziging van de) CO₂-intensiteit van de elektriciteitsproductie in de tijd stabiel is. Investerings in LE zullen de CO₂-emissies van de elektriciteitsproductie echter waarschijnlijk laten dalen, mogelijk meer dan vanuit een historisch perspectief.

Aanvullend onderzoek op dit punt kan meer duidelijkheid geven over de invloed van investering in LE op CO₂-emissies in de toekomst.

Acknowledgements

First of all, I would like to express my deepest appreciation to my supervisors, Dr. João Dias Rodrigues and Dr. Paul Behrens. Thank you for taking your time in each Thursday morning to discuss with me regarding my research progresses. The time you spent with me really provides me an new insight into how to select a good topic for PhD research and how to develop the PhD research project. I will never forget your constructive comments in my manuscripts, which help me solve lots of puzzles. Thank you for being so generous with your time, your inspiration, your guidance, and your trust throughout the years. It has been an amazing privilege to work with you!

I would like to thank my promotor, Prof. Arnold Tukker, to help me shape my exciting PhD journey. I am grateful to you for giving me the opportunity to work in CML which is surrounded by great talent and great supervision. I feel very honored and lucky to have a promotor who give me helpful feedback on my papers, and who respond to my questions and queries very timely. I am always amazed at the insightful opinions and suggestions you propose. Without your friendly assistance and innovative advice, my academic journey would not have been an interesting adventure.

I would like to thank my doctoral committee for your efforts to review my thesis and your valuable comments. Special thanks to the China Scholarship Council-Leiden University Joint Program for financial support.

Sincere thanks to Arjan de Koning, Liang Dong, Mingming Hu, Liangcheng Ye, Tao Wang, Glenn Aguilar Hernandez, Carlos Siguenza Sanchez, Laura Scherer, Carlos Blanco Rocha, Natalya Tsoy for your critical comments at the weekly meeting and nice talks after meeting. Thanks to my office-mates: Leon Hauser, Anne Uilhoorn, Bertram de Boer, Georgios Pallas, Yingji Pan, for your assistance and concern. I feel lucky to work in a wonderful office in which every member truly cares about the other. It is a pleasure to thank my other colleagues in CML: Susanna van den Oever, Joyce Glerum, Esther Negerman, Yujia Zhai, Guangchao Chen, Xiao Yunlong, Juan Wang, Zhongxiao Sun, Di Dong, Chunbo Zhang, Guiyin Wang, Qi Yu, Juan Wu, Weilin Huang, Jianhong Zhou, Daniel Arenas Lago, Angelica Mendoza Beltran, Roel Heutink, Henrik Barmentlo, Amie Corbin and Franco Donati for your kind help.

I would like to extend my thanks to my supervisor in Tianjin University, Prof. Tao Zhao, for your unwavering support and recommendation. Thanks to all my Chinese friends in Leiden and Milan. Zhengzheng Zhang, thanks for your company and encouragement. Best wishes for your PhD study. Thanks to Xiaowei Wang and Mengdan Zhang for being my best travelling partner in Europe.

I must express my extreme gratitude to my family for your sustained love, support and inspiration during my whole lifetime. Special thanks to my parents for encouraging me to pursue my dream. Finally, thanks to my husband who I still have never met enabling me to focus on the PhD journey.

Thanks again for your help.

List of publications

Rong Y, Behrens P, Rodrigues JFD, 2018. The evolution of inter-sectoral linkages in China's energy-related CO₂ emissions from 1997 to 2012. *Energy Economics* 69, 404-417.

Rong Y, Rodrigues JFD, Behrens P. Impact of non-fossil electricity on the carbon emissions embodied in China's exports. *Journal of Cleaner Production* (submitted on August 2017, accepted with major revisions).

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Curriculum Vitae

Rong Yuan was born on 25th April 1990, in Urumqi, Xinjiang, China. She took her high school education from Urumqi No.1 Senior High School during 2005-2008. After graduating with a bachelor degree in Beijing Forestry University in June 2012, she became a PhD student in Tianjin University in September 2012. From 2014-2015, she studied at Politecnico di Milano, Italy as a visiting PhD student. She joined the Department of Industrial Ecology of Institute of Environmental Sciences (CML) of Leiden University in 2016 with the support of the China Scholarship Council. At CML, she undertook a PhD project on the application of MRIO models to analyze the carbon impact of low-carbon electricity development in China under the supervision of Dr. João Dias Rodrigues, Dr. Paul Behrens and Prof. Arnold Tukker. This thesis is the outcome of her PhD research.